Limits of Life in the Atacama Desert

Scientific Investigation and Robotics Experiments

Red Whittaker
David Wettergreen
The Robotics Institute
Carnegie Mellon University

Preview

- **Science Investigation**
- **Technology Challenges**
- **Atacama Experiment 2003**
- **Continuing Research 2004**

Atacama Desert

Atacama Desert in northern Chile lies between the Pacific and the Andes

Driest desert on Earth

- No measurable rain or snow in some regions but
  - Fog from the Pacific
  - Runoff from the Andes

Analogous to Mars

- Arid, High UV, Soil Oxidants

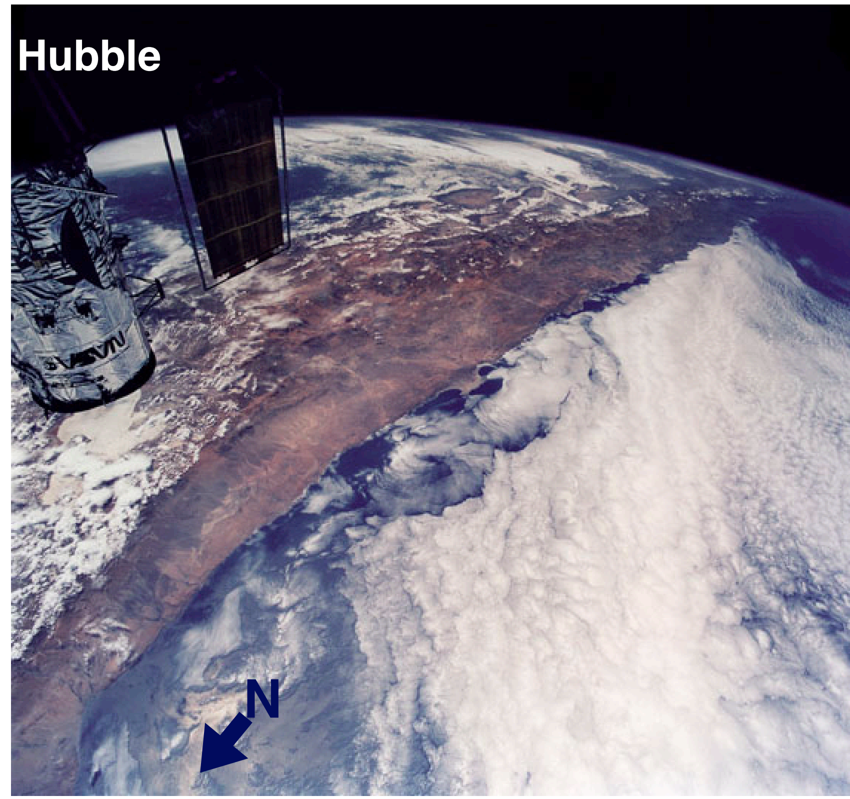
Interior Desert

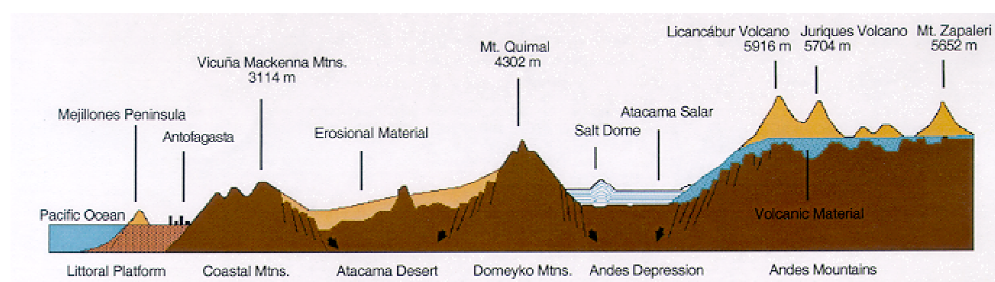
Desert rises from Coastal Range (700m) to the Altiplano (4000m)

- **Moisture blocked by Pacific atmospheric pressure and the Andes**

Most lifeless on Earth?

- **Absolute desert evidenced by the absence of biogenic organic molecules?**





Coastal Range

Parallels the Pacific coast

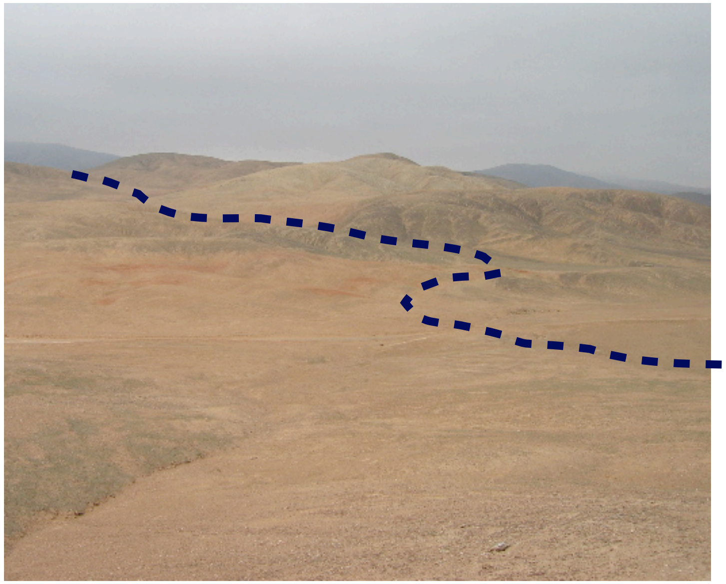
- **Camanchacas (salt fogs) occasionally penetrate inland through mountain range**

Desiccation-tolerant organisms detected in microhabitats

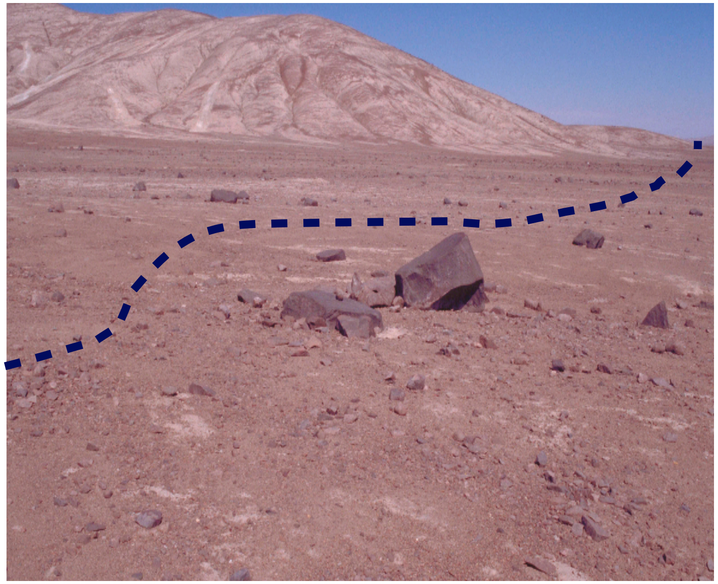
Scientific Investigation

Biodiversity and distribution of habitats in Atacama subregions are not understood

- **Where does life survive and where does it not?**
- **What factors govern the distribution?**



Coastal Range

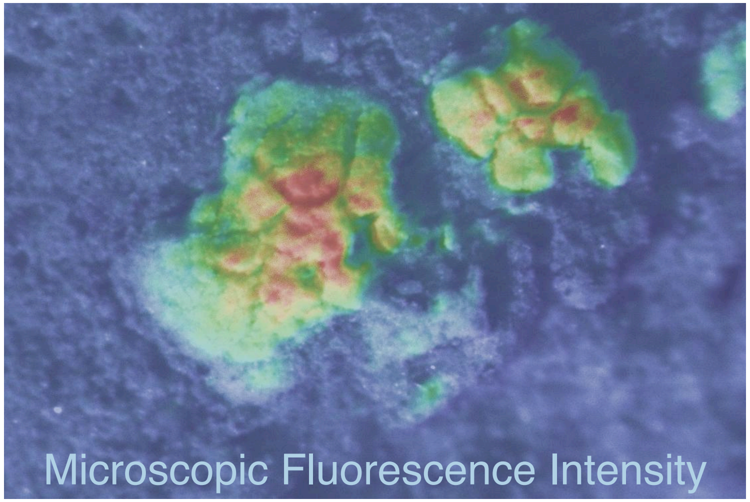


Interior Desert

Science Objectives

Seek Life

- **Detect life unambiguously**
- **Characterize biota surviving in the Atacama**
- **Measure spatial variability of biodiversity**
- **Detect environmental boundary conditions of microorganic life**



Science Objectives

Seek Life

Understand Habitat

- Characterize the physical environment
- Examine current biological oases and microorganic communities
- Determine geologic and environmental conditions of identified current habitats
- Measure spatial diversity and types of habitats for microorganic life

Science Objectives

Seek Life

Understand Habitat

Make Relevant Measurements

- Integrate and field-test instruments that form an appropriate science payload
- Make measurements that motivate the exploration of analogous environments on Mars
- Develop methods and procedures for conducting long-distance science surveys

Science Instruments and Purpose

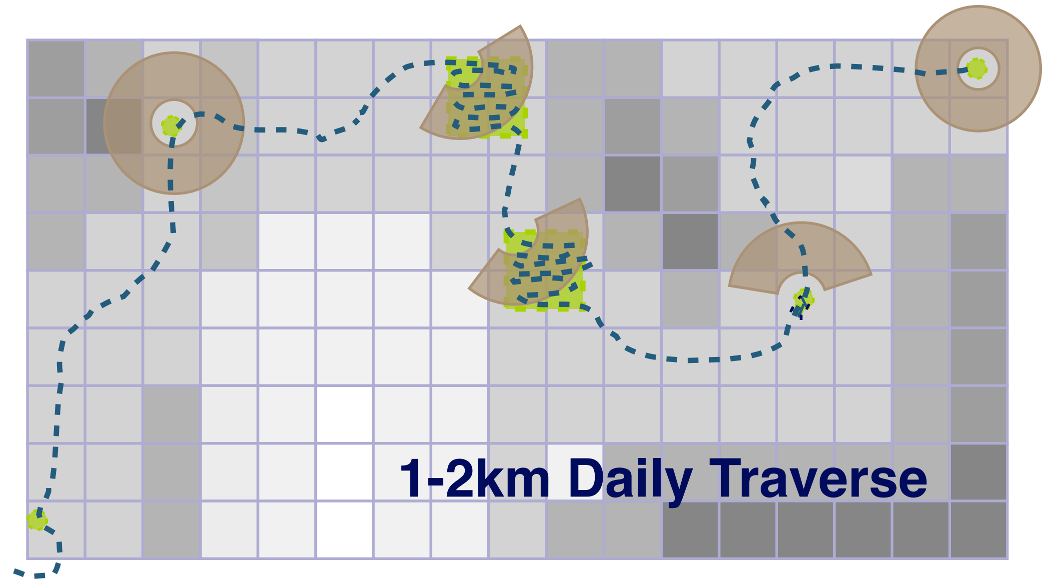
Payload	Purpose
Fluorescence Imager	Obtain macroscopic images of natural fluorescence for gross detection of chlorophyll. Identify the presence of photosynthetic organisms and estimate their abundance. Assist in identifying the presence of life
Fluorescence Microscope and Dye Probes	Obtain microscopic fluorescent/visible light images of colonies of photosynthetic microorganisms. Image additional bands to detect successful binding of fluorescent dyes (to detect carbohydrates, lipids, proteins). Image fine-scale morphology and texture of microorganisms. Determine the presence of life and count abundance.
Visible/Near-IR Spectrometer	Determine mineralogy. Establish conditions of the habitat and detect aqueous materials that may provide climate and biologic evidence
Stereo Panoramic Imager (SPI)	Investigate geologic setting and processes and allow morphological, geological, and topographical characterization of the environment. Assist rover navigation and designation of science targets.
Environmental Sensors	Observe weather and incident sunlight for possible correlation with biotic processes and habitat features. Measure temperature, pressure humidity, wind, insolation, UVA/UVB.
Subsurface Access Mechanism	Expose and present subsurface sands and soils and overturn rocks

Scientific Approach and Metrics

Survey Traverse

To understand distribution of life and habitats a survey is necessary

- **Collect large number of survey samples during daily kilometer-long traverse**
- **Conduct limited focused sampling with shallow subsurface access and nighttime micro-fluorescence**



Yr	Activities	Duration (50% Ops)	Distance	Samples	Location
03	Component Testing	30 days	10 km	10 Survey Samples	Coastal Range A
04	Functional Integration	60 days	50 km	100 Survey Samples 10 Focused	Coastal Range B Hyper Arid A
05	Operationa l Science	100 days	180+km,	160+ Survey Samples 16+ Focused	Coastal Range C Hyper Arid B Transition A

Robotic Astrobiology

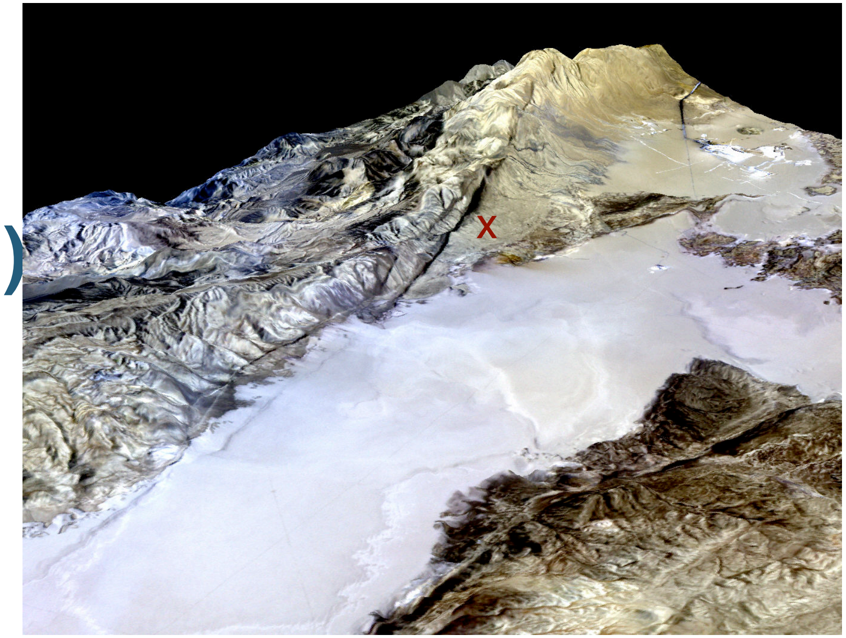
Our operational hypothesis is that planetary astrobiology requires extensive mobility

- Tens of kilometers to measure biodiversity
- Long-distance mobility drives the design of rover and software
- Autonomy is an implicit requirement in a resource-poor situation

Factors motivating autonomy:

- Rover responsiveness
- Resource utilization
- Mission duration
- Operation costs
- Instrument operation
- Sampling frequency
- Command complexity
- Communication bandwidth and delay

Robotics Challenges



Navigate Over the Horizon

- Navigate beyond the robot field-of-view (>1km)
- Model the environment and detect obstacles at necessary scales
- Localize based on odometry, sun position, and local feature/global landmark tracking (but not artificial satellites)
- Register observations to orbital datasets and limit position error to 5% of distance traveled

Robotics Challenges

Navigate Over the Horizon

Autonomy and Self-Awareness

- Establish variable rover autonomy and effective remote investigation (telescience) over low-bandwidth, long-latency communication links
- Develop rover self-awareness, monitoring hardware and software elements, for fault detection and recovery
- Achieve multi-day unattended operation and greater than 1 km traverse per command cycle

Robotics Challenges

Navigate Over the Horizon

Autonomy and Self-Awareness

Use Resources Efficiently

Enable onboard, resource-limited traverse planning and sequence execution to address:

- Power: Solar and battery power and overnight hibernation
- Communication: Cycles, delay, and data volume
- Science: Instrument use and sampling requests

Robotics Challenges

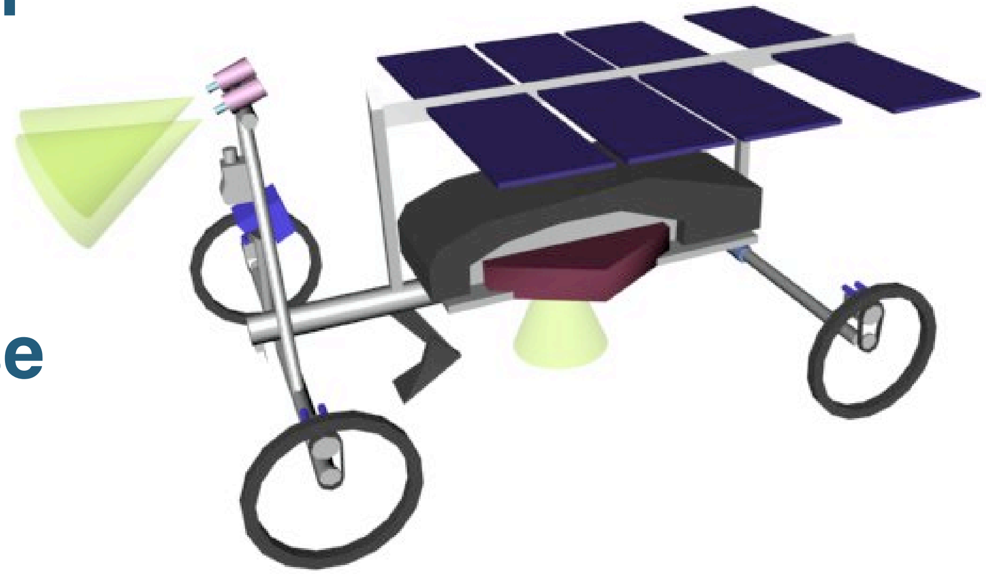
Navigate Over the Horizon

Autonomy and Self-Awareness

Use Resources Efficiently

Create a Robotic Astrobiologist

- **Deploy life-detection instruments with an rover capable of of long-distance autonomous traverse**



Technical Approach and Metrics

Research technologies for navigation and autonomy that build upon prior research

Develop and integrate new capabilities for validation and verification in controlled field experiments

Measurable results, not just distance measurement but distance, time, and fault statistics

Evolve:

- component testing, 2003
- functional integration, 2004
- operational science, 2005

Yr	Activities	Duration (50% Ops)	Distance	Samples	Location
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Prior Research and Experiments

Atacama Desert Trek 1997

- Demonstration of long-distance traverse
- 220 kms of travel on the Llano de la Paciencia near Salar de Atacama
- eration and autonomy (with in)

Nomad in Chile

Fossilized stromatolite detected remotely

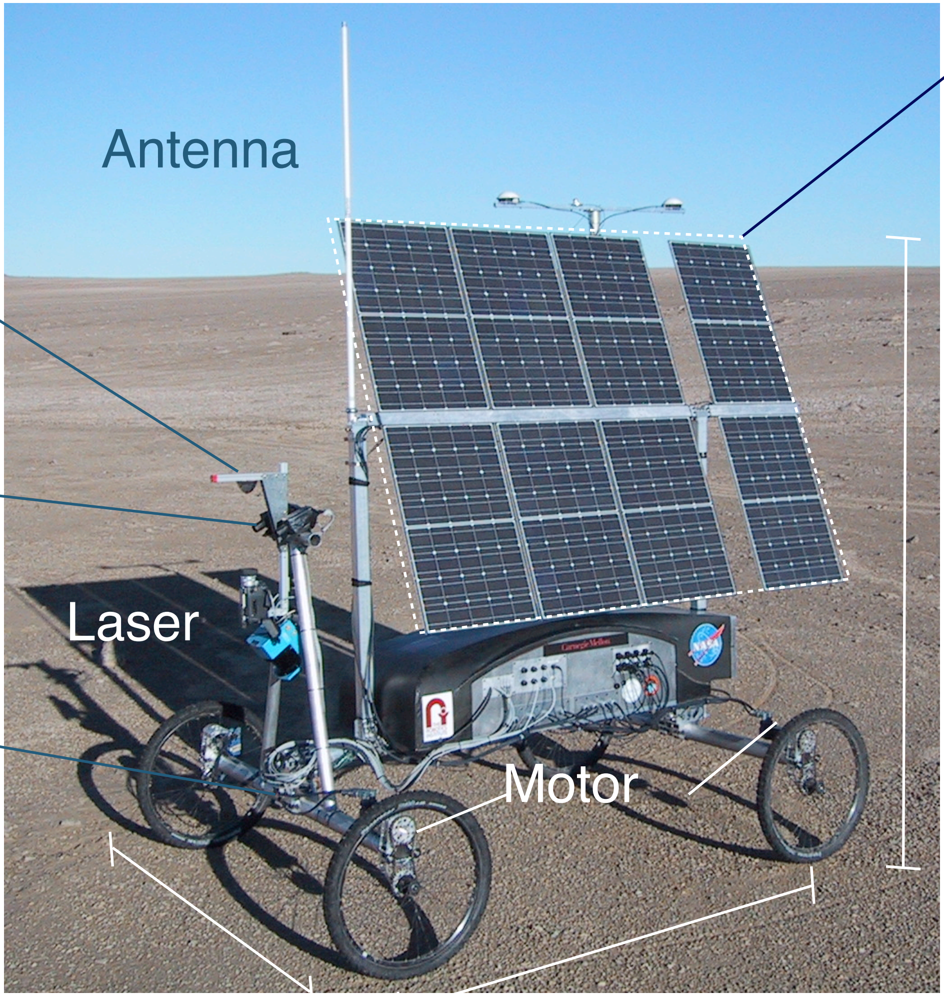
Prior Research and Experiments

Sun-Synchronous Navigation, 2001

Robotic navigation with reasoning about sun position for sustained exploration

Hyperion on Devon Island
24-hour Solar-powered Traverse

Polar Rover

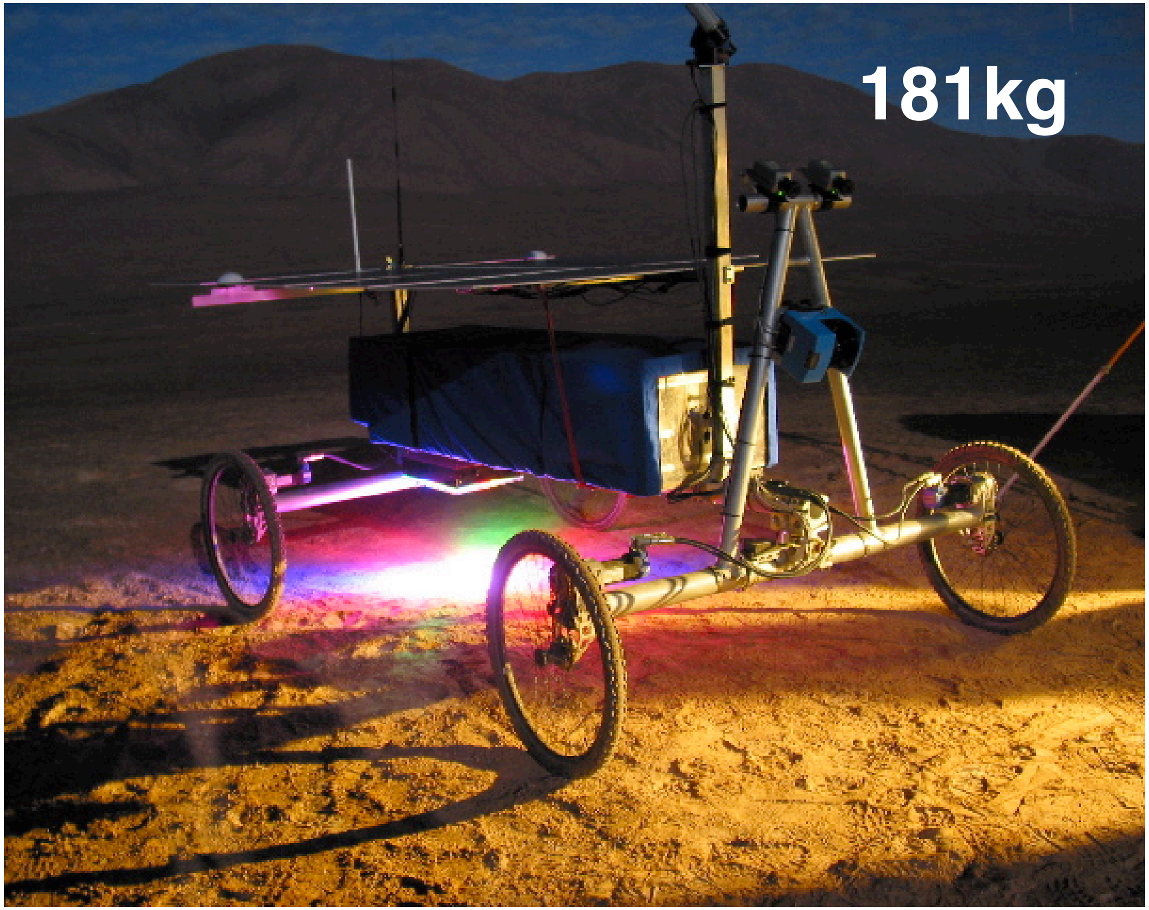


Antenna
Mirror
Cameras
Laser
Pivot
Motor
3.5m2
2.2m
1.8m
2m
156kg

Desert Rover

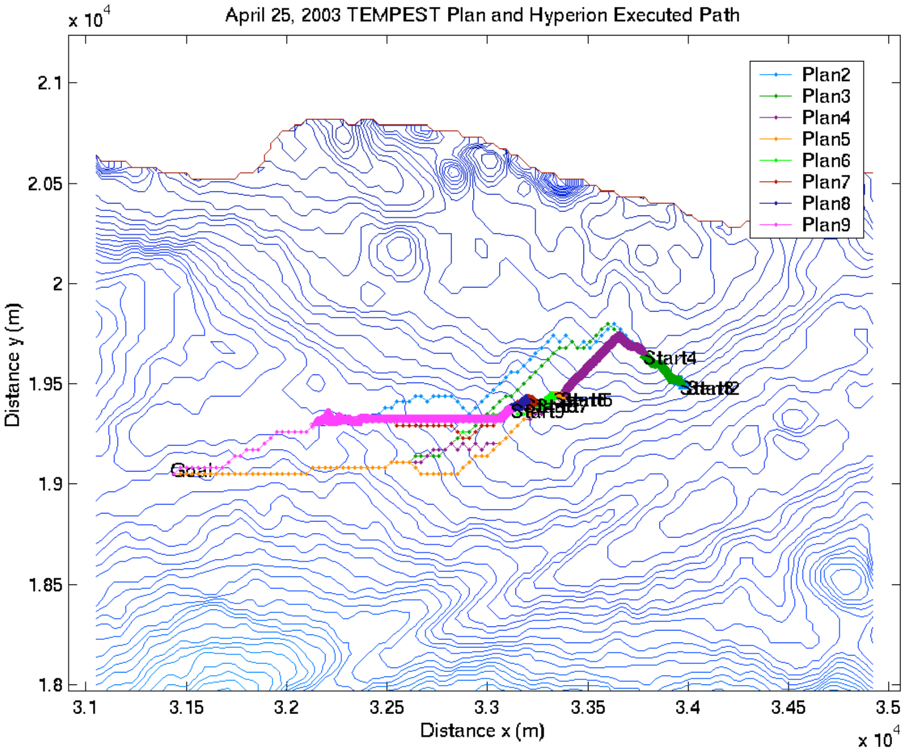
Changed panel to horizontal, laser to vertical, cover to cloth

Added roll/pitch sensor, radios, gyroscope, power sensors, sun sensor, mast, panoramic and side camera, fluorescence imager



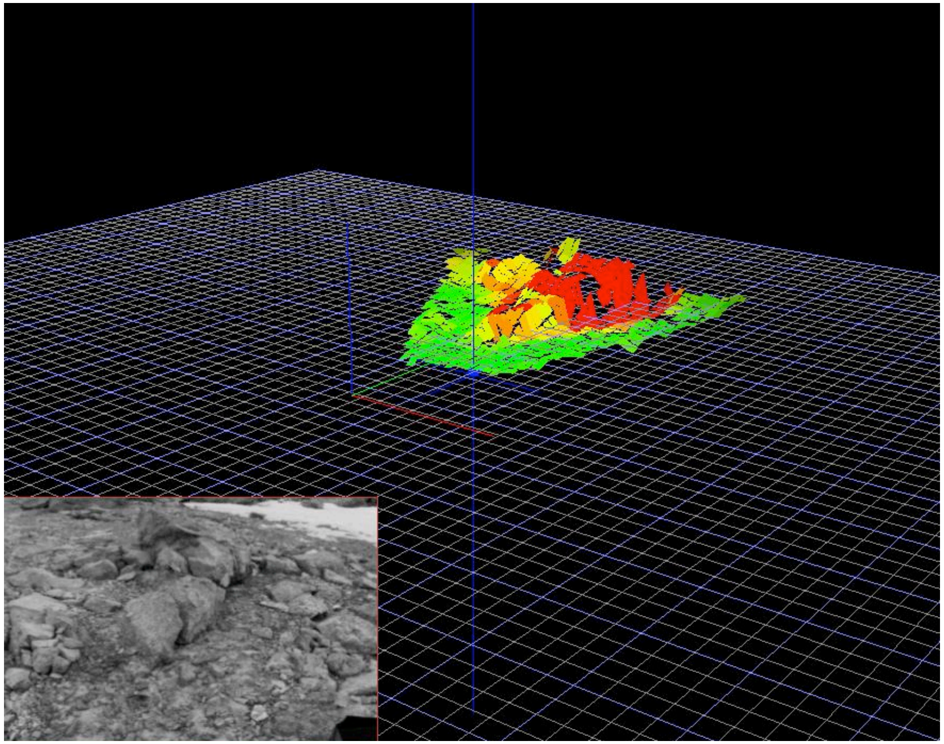
Mission Planning

- **Model the environment (terrain and solar) and vehicle (power and mobility)**
- **Estimate the resources (power) required to reach the goal**
- **Optimize schedule and path to expend minimum and acquire maximum resources**
- **Execute path and replan as necessary**

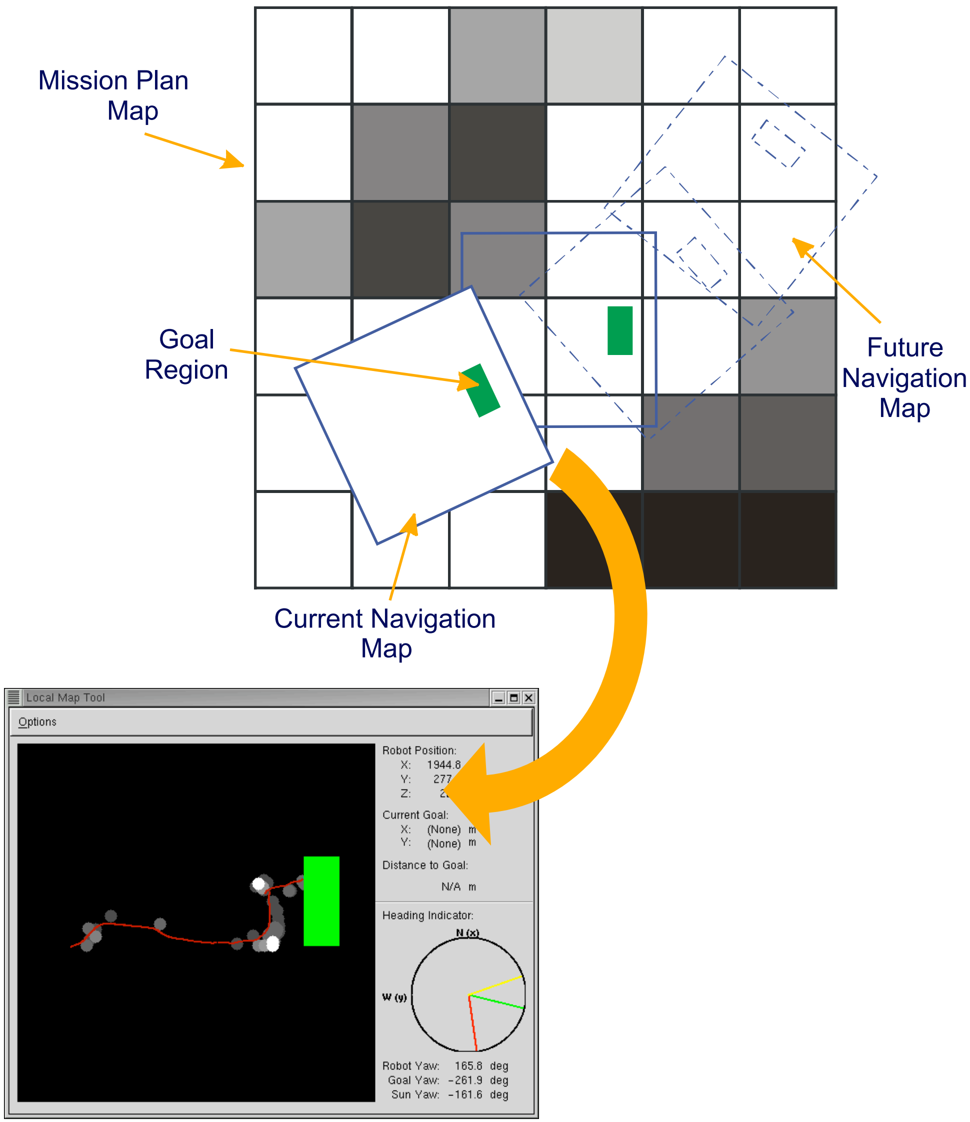


Terrain Evaluation

- Terrain model developed from depth image using region-based correlation method
- Terrain evaluated by fitting vehicle footprint to terrain
    - Slope
    - Elevation discontinuity
    - Roughness (residual)
- Each metric linearized [0,1] and maximum cost assigned to location



Rover Navigation

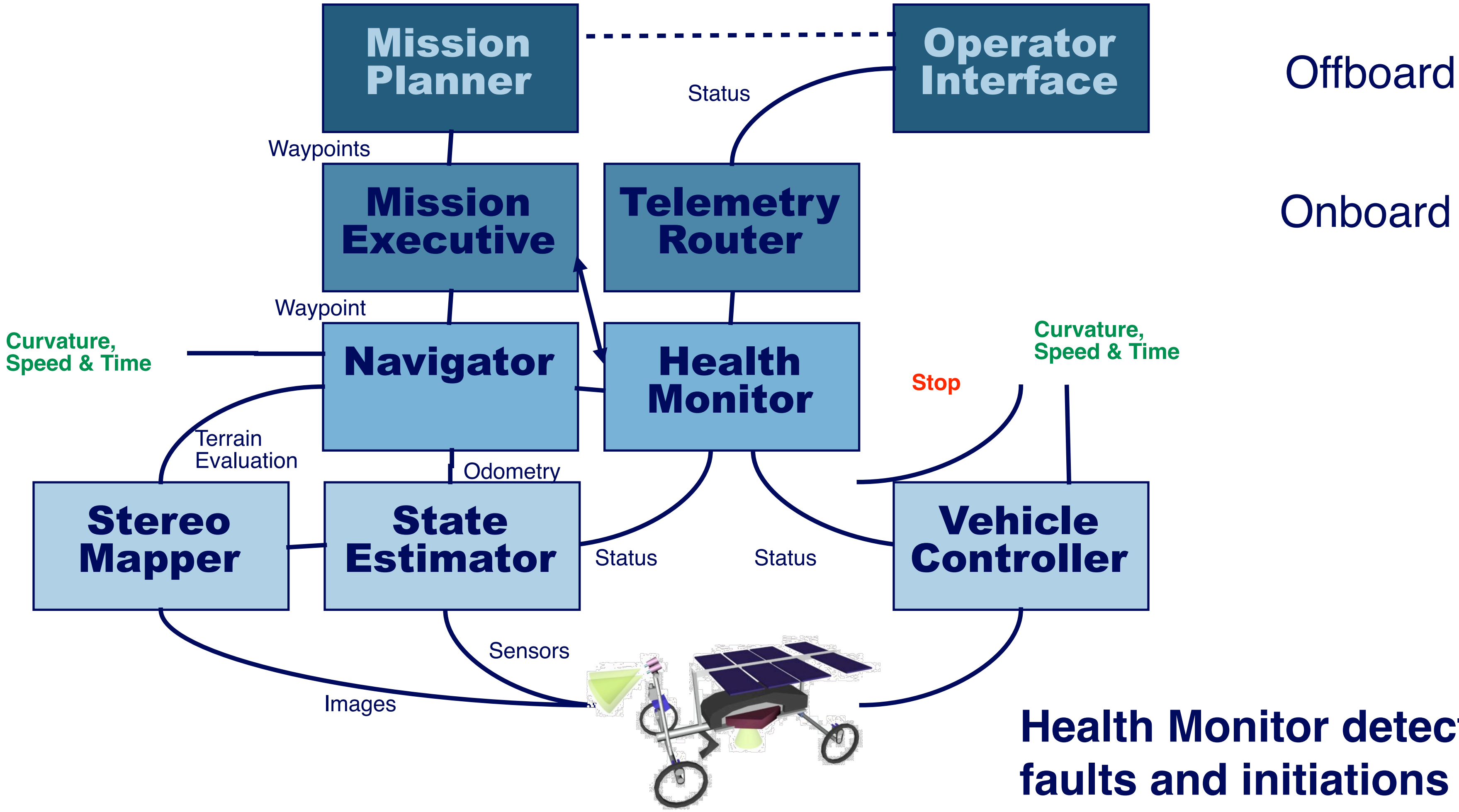


Navigator operates on composite terrain evaluation map

Utilize onboard sensing to avoid near-field obstacles and allow continuous motion

Select arcs based on cost, speed, and goal location

Rover Architecture



Health Monitor detects faults and initiations recovery behaviors

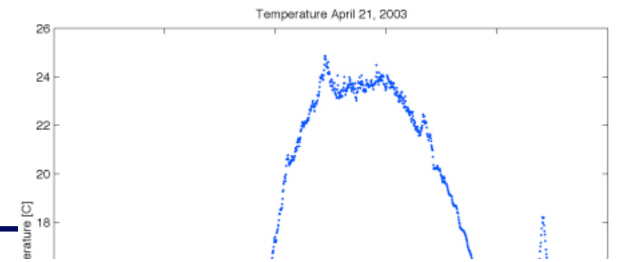
Atacama Experiments 2003

- **Conduct preliminary science investigation**
  - Collect data
  - Evaluate science instruments
- **Measure rover performance**
  - Solar, Mobility, Solar, Perception, Navigation, Localization, Communication, Autonomy, Environmental Conditions
- **Specify requirements for a capable astrobiology rover**

Hyperion in the Atacama

Field Site

Environment



Purpose:

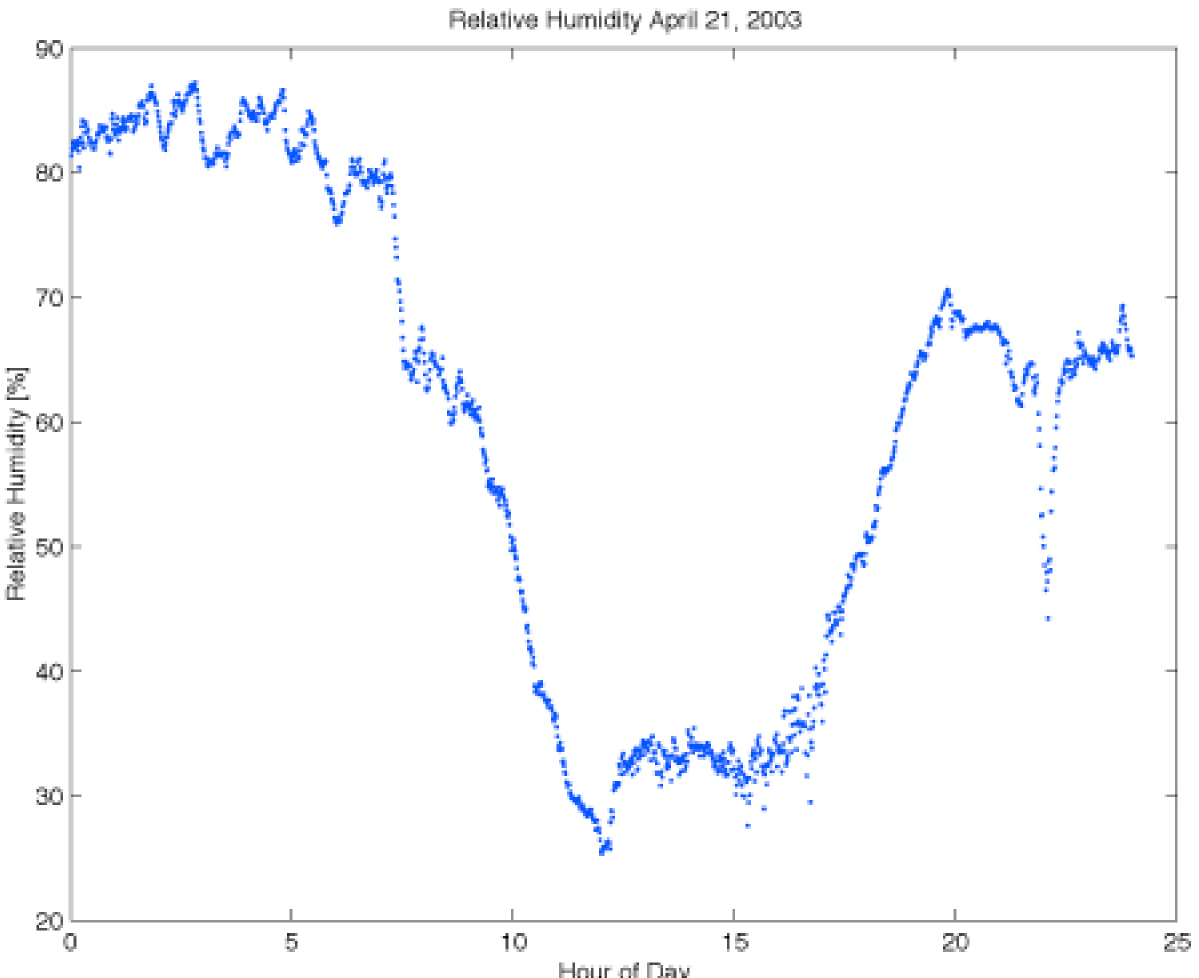
- **Test environme for science**
- **Understand des for desert rover**

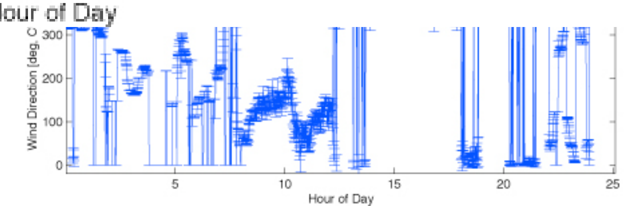
Measure:

- **Temperature, hu**

Results:

- **Daily variation i**
- **Sustained afteri**





Solar Flux

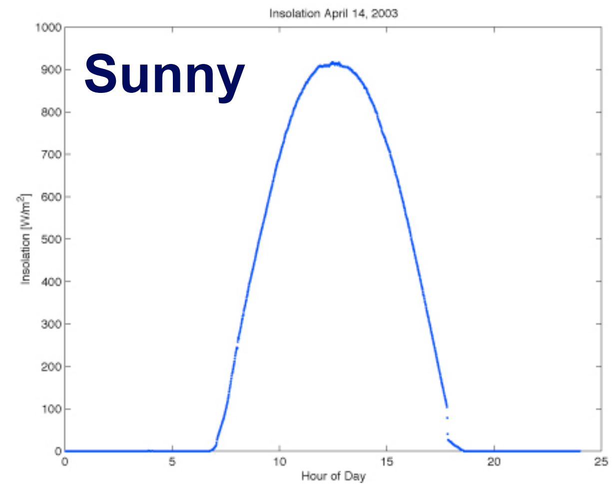
Purpose:

Obtain full-spectrum insolation data

Measure:

Solar flux with photospectrometer

Si and GaAs cell performance under load conditions with various pointing

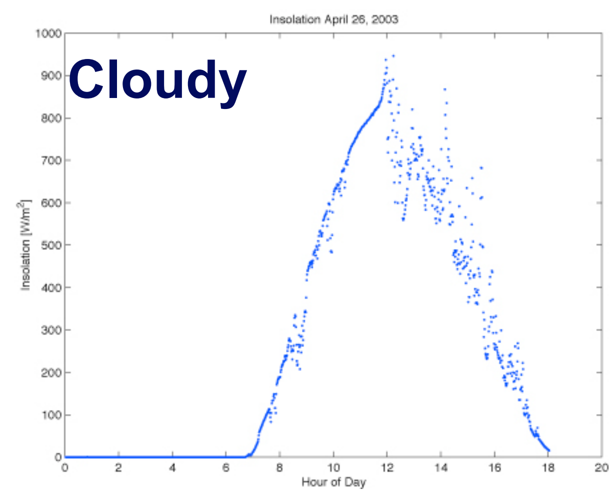


Results:

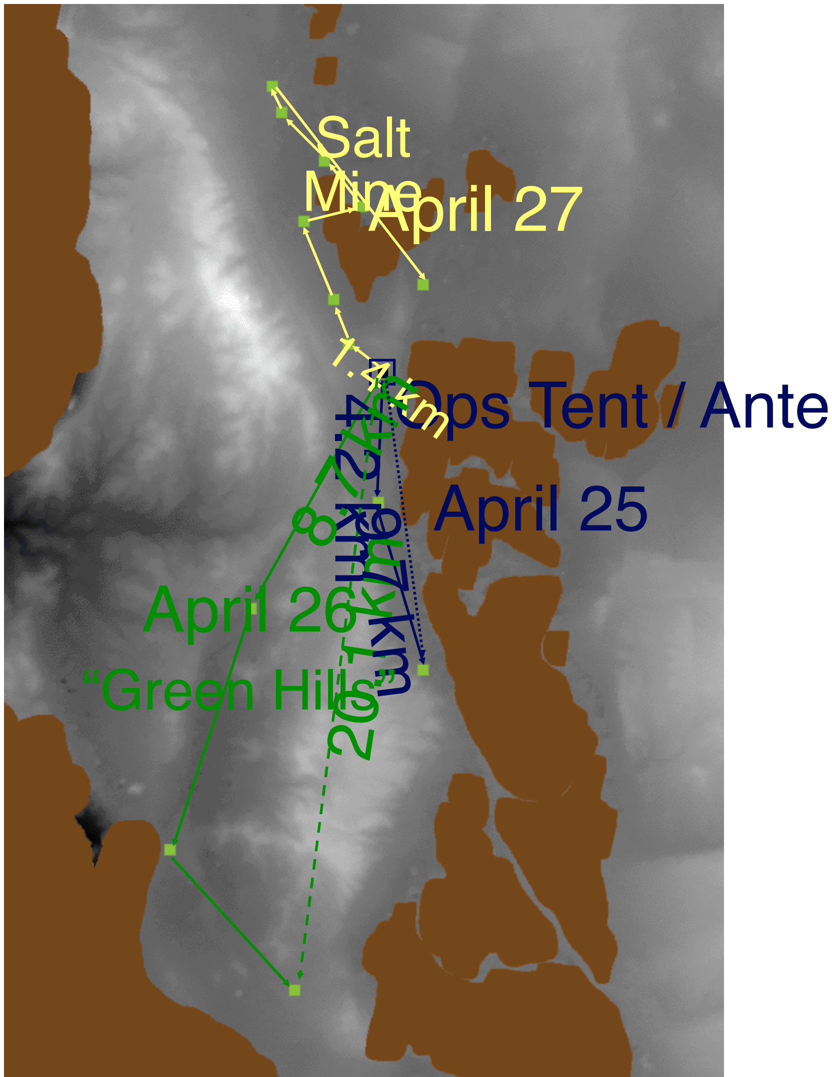
High peak insolation (900W/m^2) but rapid drop off

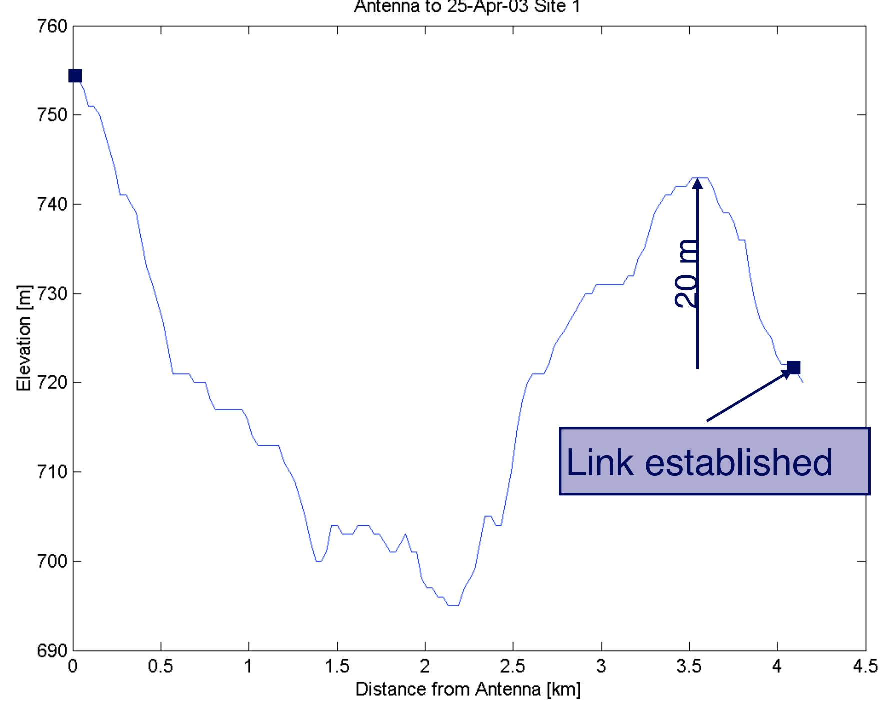
Significant cloud impact

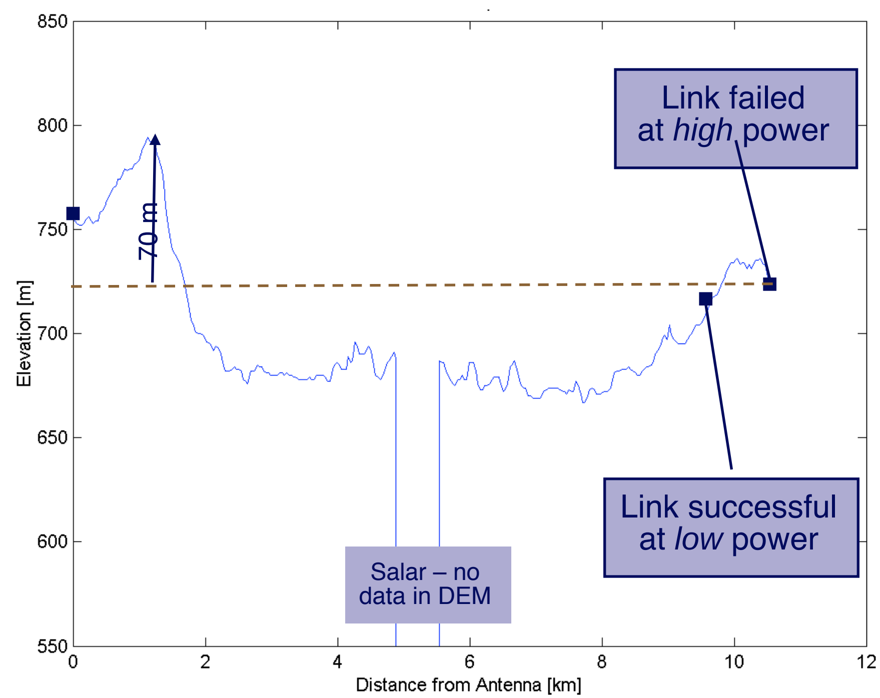
Rover in power deficit with Si cells/Pb-Acid battery



Communication







Terrain Perception

Purpose:

Obtained detailed imagery and calibrated terrain models to develop navigation algorithms

Measure:

Obtain calibrated stereo pairs with ground-truth

Repeat in terrains of varying obstacle density

Result:

Over 20Gb of imagery and telemetry for analysis

Camera exposure control must be dynamic

Far-field navigation will be new navigation research

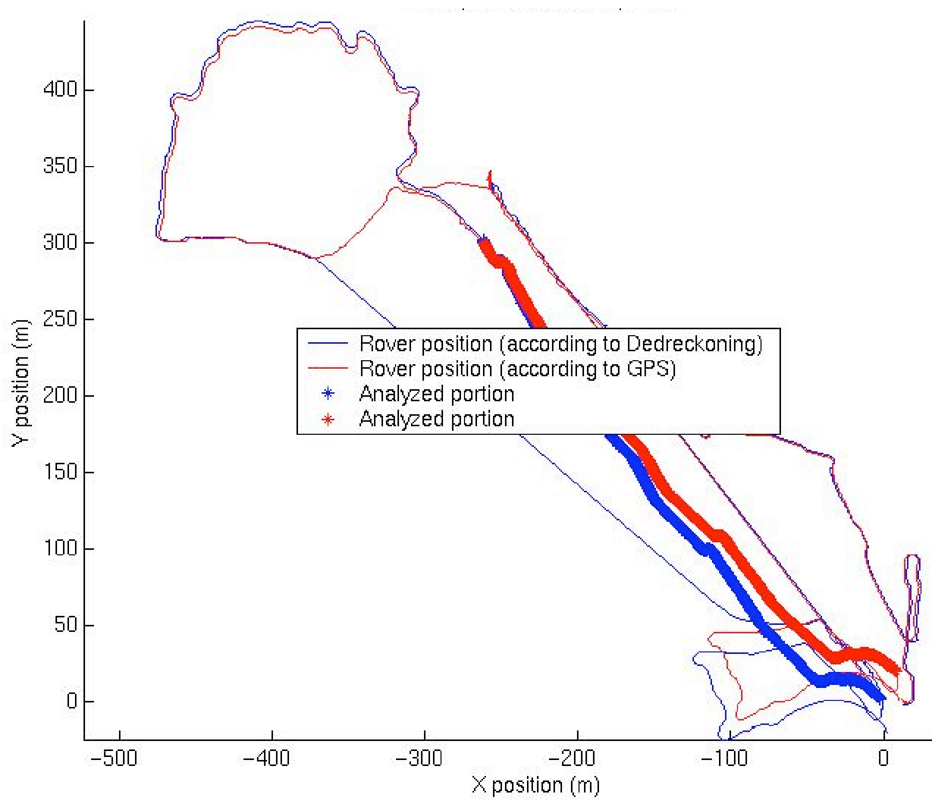
Localization

Purpose:

- Obtain image sequences and ground truth to develop localization algorithms
- Test rough terrain dead reckoning

Measure:

- Forward stereo, sid
- and panoramic view
- Rover telemetry and ground truth



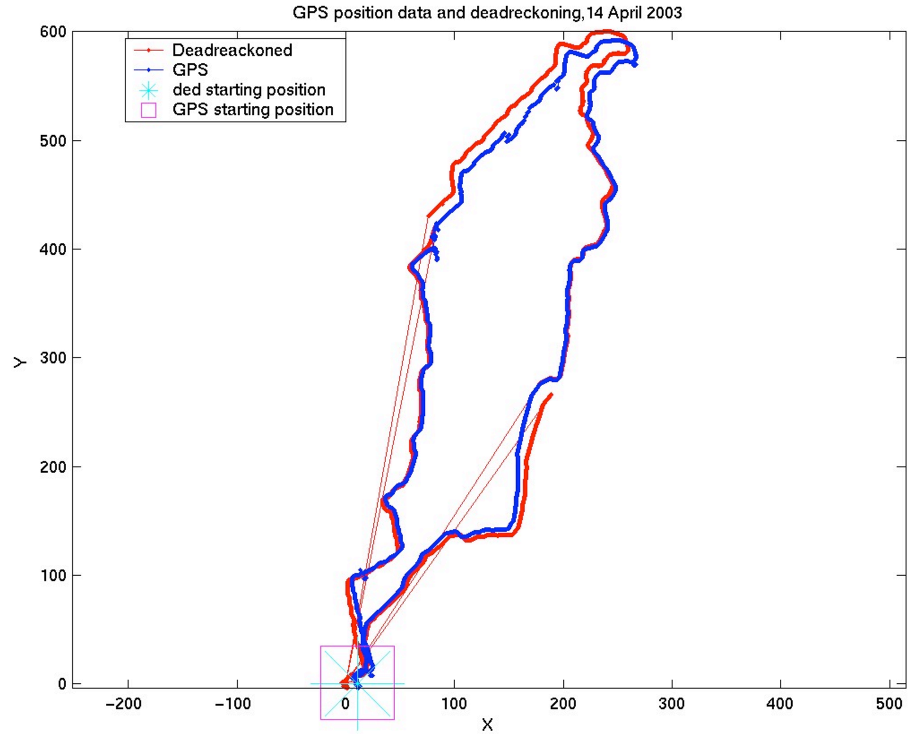
State Estimation

Method:

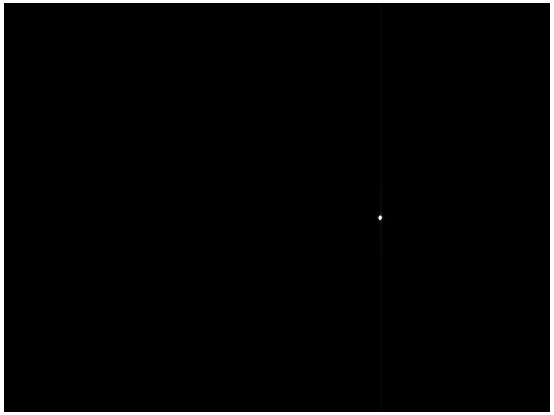
- **Single axis fiber-optic and dual wheel encoders to estimate direction and distance of motion**
- **Roll and pitch inclinometers to measure gravity vector**
- **Piecewise integration to estimate position**
- **Independent of GPS**

Result:

- **Error 3 - 5% of distance traveled with proprioception**



Sun Tracking



Purpose:

Test sun sensor and collect data for algorithm development

Collect:

Sun image sequences from moving and stationary vehicle and correlate with ground truth

Result:

Non-linear smoothing on orientation estimate will improve localization and correct gyro drift

Mobility and Locomotion Power

Purpose:

- Refine vehicle mobility and power models
- Understand design drivers for desert rover

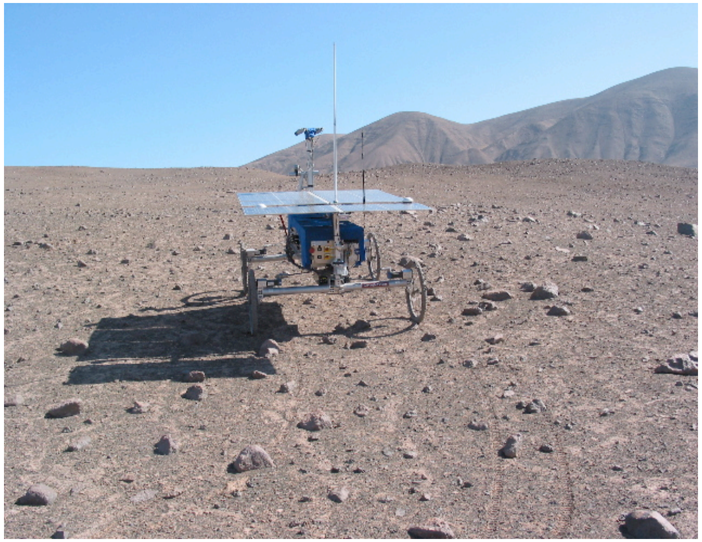
Measure:

- Instrument solar array, battery, and motor voltage and current
- Collect continuous data over variety of terrain
- Test vehicle at limits of mobility performance

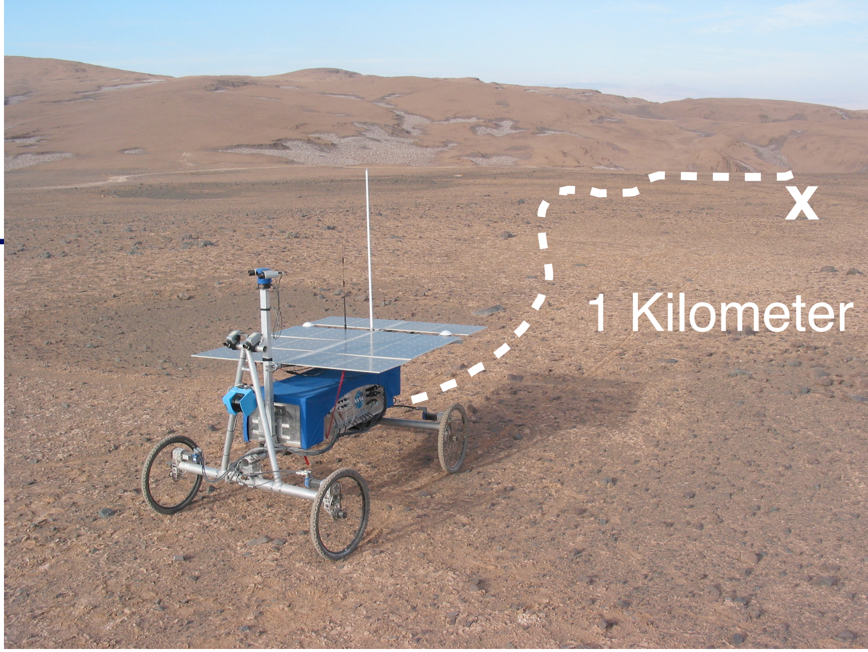
Result:

- Difficult to isolate individual effects
- Hyperion speed and torque are insufficient

Mobility and Locomotion Power



Integrated Operation



Purpose:

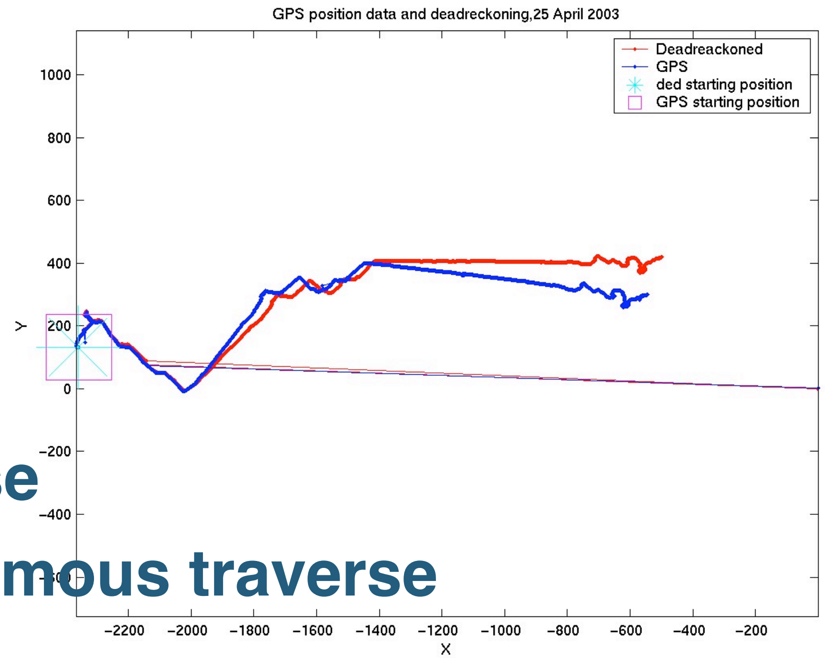
Validate navigation approach

Identify research priorities

Conduct:

Traverses in relevant terrain

- Without prior information
- With autonomous navigation
- With relevant comm & power



Result:

18kms of autonomous traverse

Single command, 1km autonomous traverse

Rover Traverse

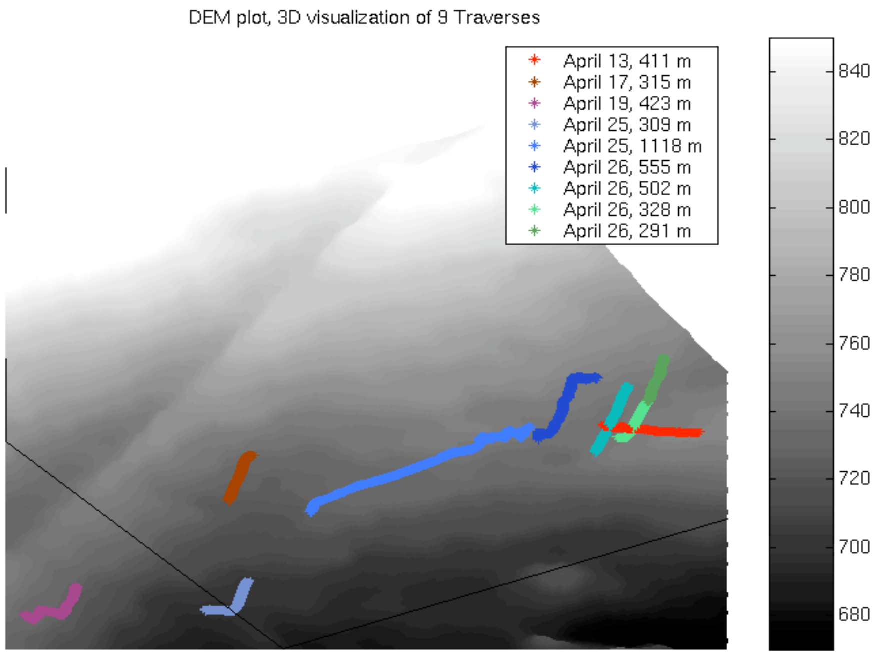
Autonomous traverse initiated by single command of goal location

90 autonomous traverses conducted

- **Average distance 20m**
- **8 longer than 300m**
- **1 longer 1km (1118m)**

Average speed 0.25m/s

Common traverse-ending faults: roll/pitch limit, n path ahead, off schedul



Stereo Panoramic Imager

Purpose:

- Confirm operation in the field
- Collect preliminary science data

Collect:

- Complete panoramas
- High-resolution imagery correlated to instruments

Result:

VIS/IR Spectrometer

Purpose:

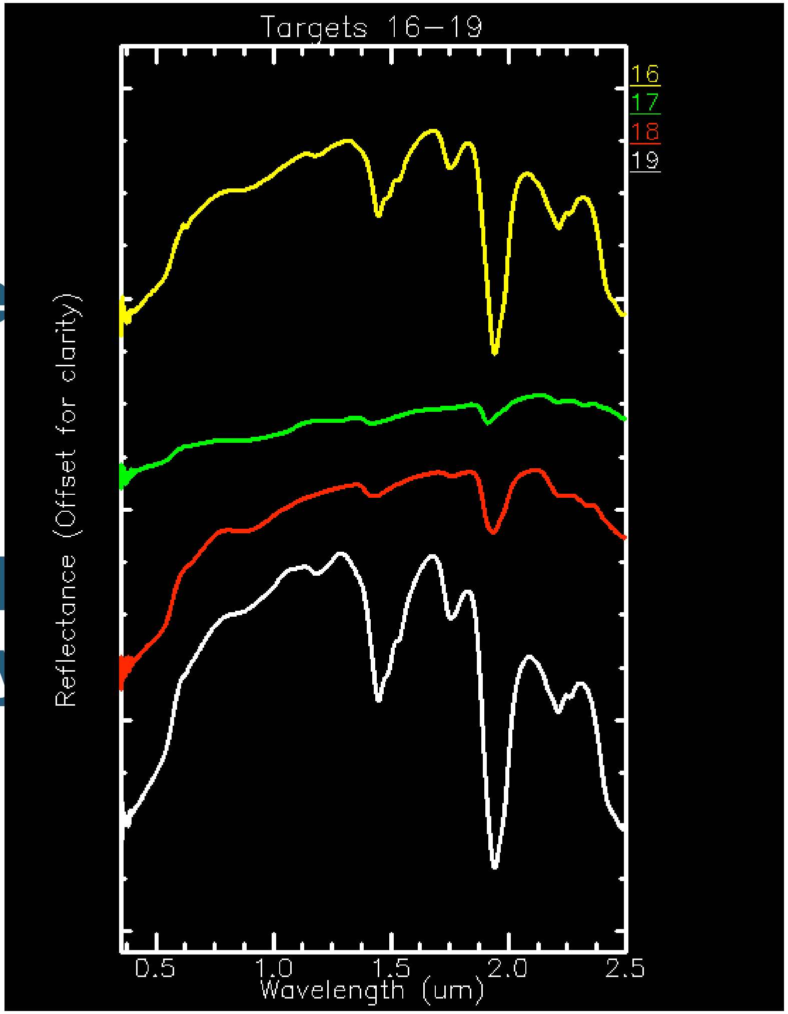
- Confirm use in the field
- Collect preliminary science data sets

Measure:

- VIS/IR spectra of rocks and soil correlated with imagery

Results:

- Validated for field use
- Instrument placement accuracy and localization



Fluorescence Imager

Purpose:

- Confirm use in field
- Collect preliminary science data sets

Measure:

- Fluorescence of rock, soil and organisms with portable unit

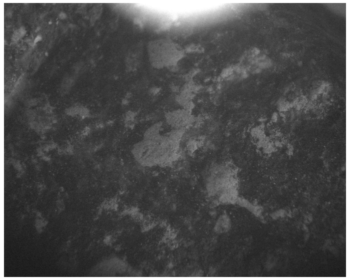
Result:

- Focus and lighting need refinement
- Detected chlorophyll fluorescence in samples

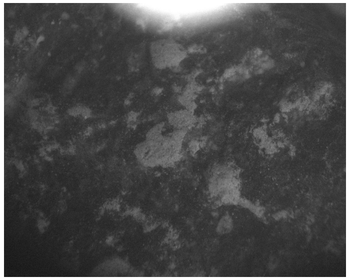
Fluorescence Microscope

- **Field validation of fluorescence microscopy**
- **Future rover integration**

Visible



450nm at 660nm



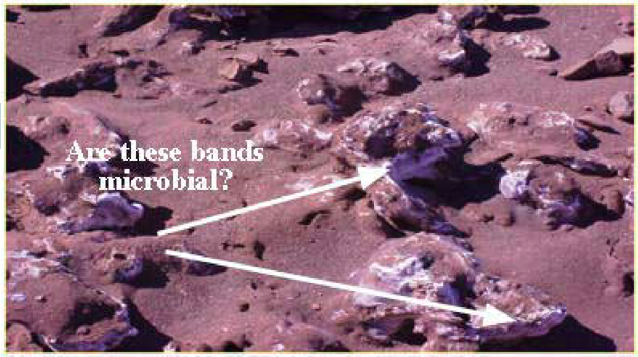
620nm at 660nm

Preliminary Science Investigation

Remote detection of life inconclusive (this year!)

- Examined 26 samples (image, spectra, microscopic fluorescence)
- Insufficient correlated evidence

Remote investigation of habits



- Comparison term-by-term to ground truth shows that geological units and environmental components correctly interpreted
- Some results in mineralogy more precise than ground-truth team due to spectral capabilities

Ground-truth field investigation

- Identified the significance of microhabitat
- Detected interesting “troglodyte” fungi on underside of gypsum surface crust

Education and Public Outreach

Life in the Atacama is employing the EventScope project to support earth science education and broad public outreach

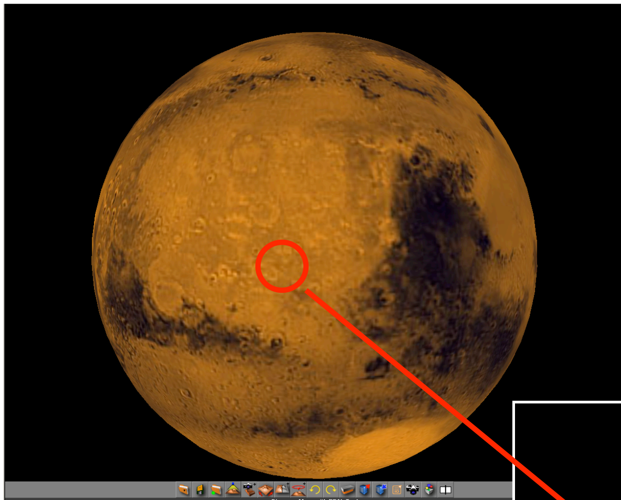
EventScope creates “virtual environments” of Mars and the Earth created with:

- **Satellite pictures**
- **Digital elevation models (DEMs)**
- **Images and instrument data collected by rovers**

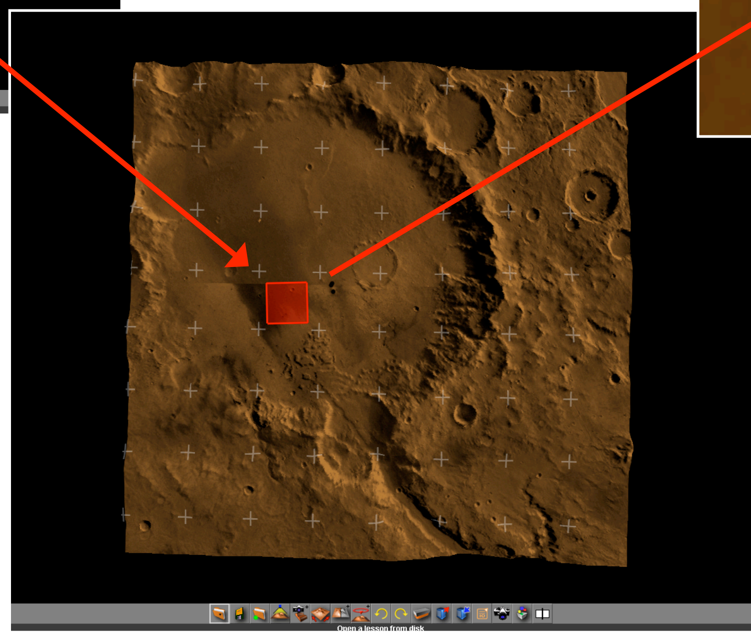
School students and the public can use EventScope to virtually explore distant places

EventScope is being used at museums and science centers to engage and educate the public

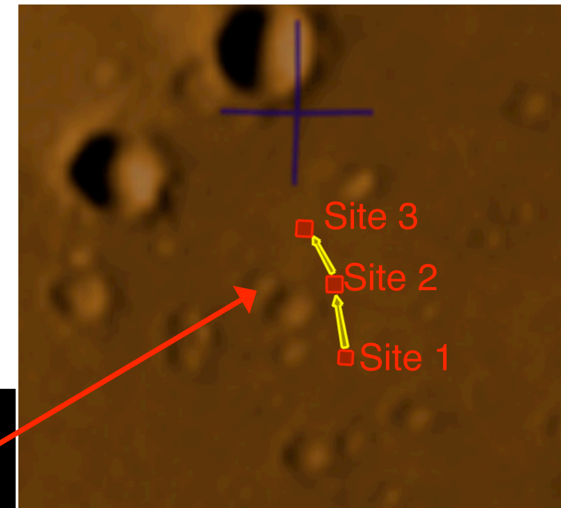
EventScope: Mars



Explore from orbit

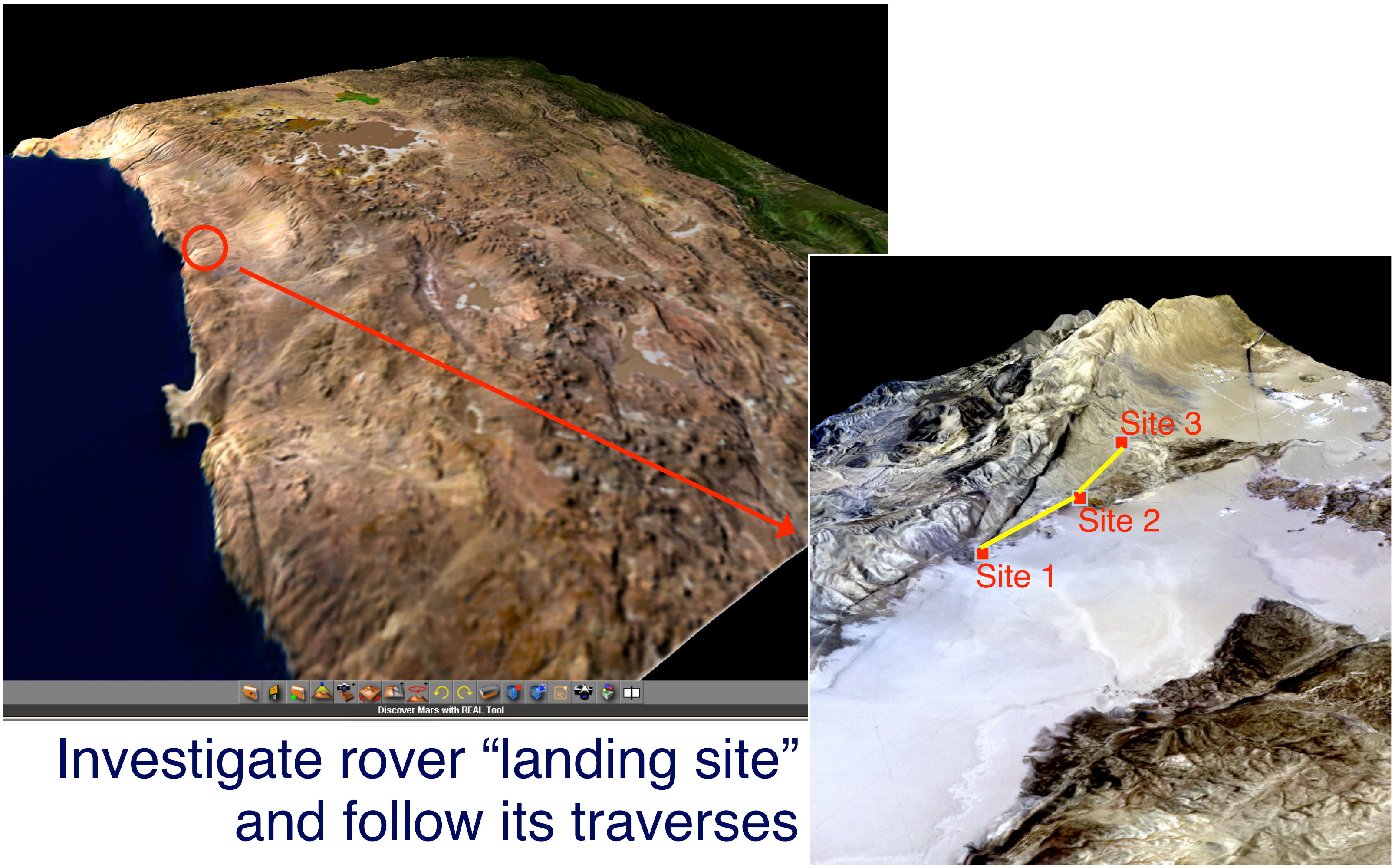


Investigate MER landing sites



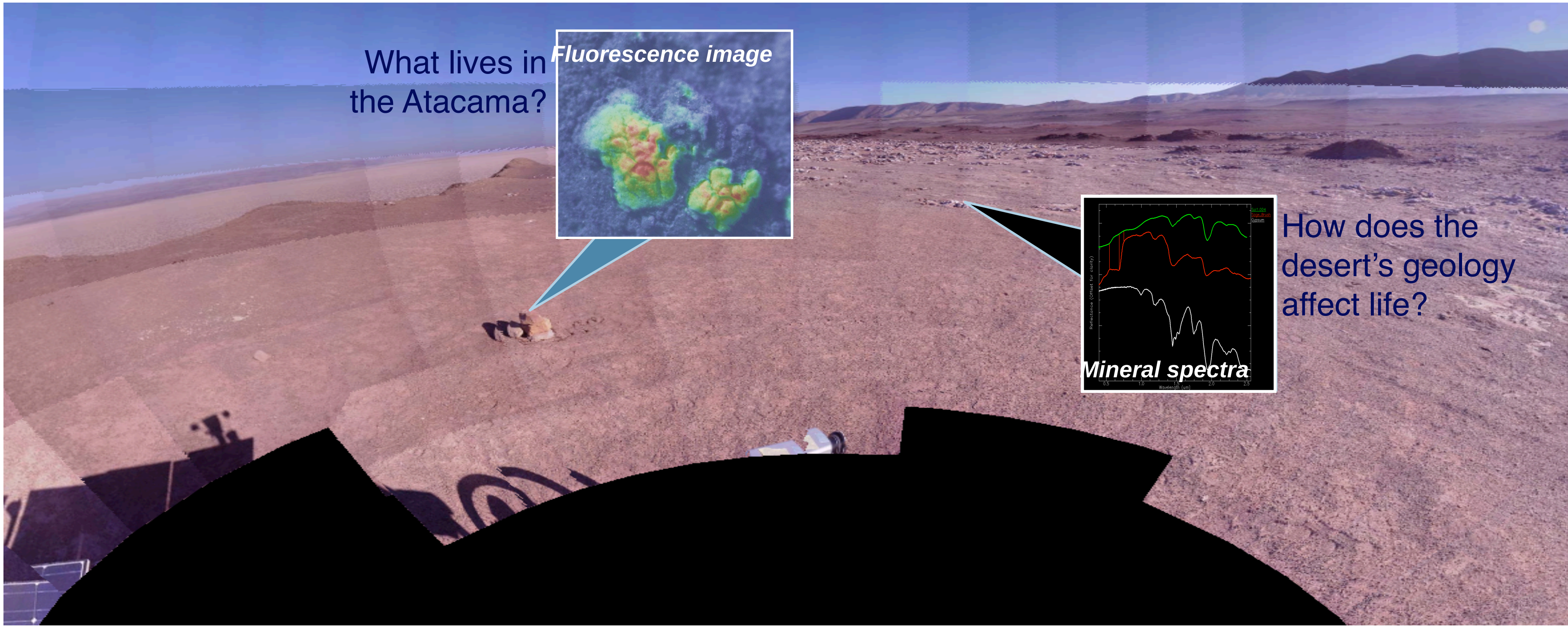
Follow the rovers

EventScope: Atacama



Investigate rover “landing site” and follow its traverses

EventScope: Atacama



EventScope will display the latest data from the Atacama rover to museums and over the Internet

Allow the public throughout the world to learn about robotics and astrobiology

Current Robotics Research

Desert Rover Refinement

- Energy-efficient, terrain-capable rover with "plow"

Mid-range Terrain Evaluation

- Evaluate mid-range (5-30m)

Fault Detection and Recovery

- Fault diagnosis and recovery

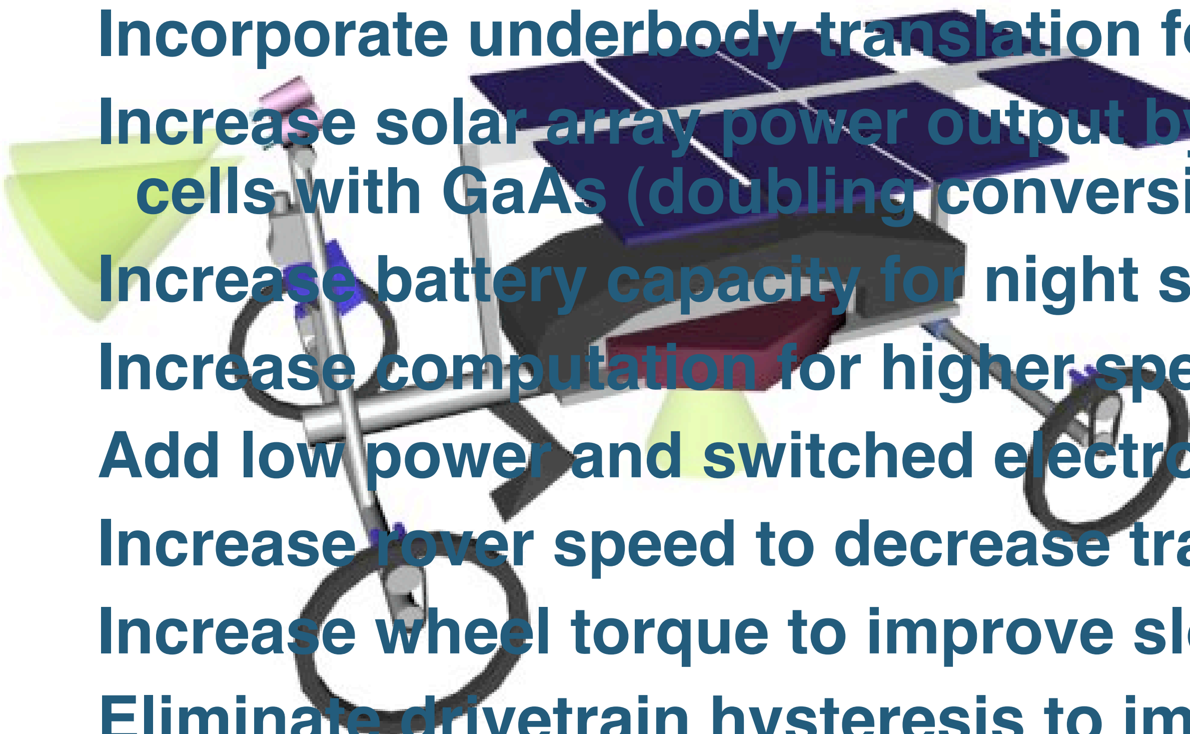
Mission Plan Execution and Replanning

- Planning for communication and science
- Resource-cognizant mission executive

Desert Rover Refinement

Energy-efficient, terrain-capable rover for desert traverse

- **Hyperion reconfiguration design drivers**
- **Accommodate science instrument payload**
- **Incorporate underbody translation for imager**
- **Increase solar array power output by replacing Si cells with GaAs (doubling conversion efficiency)**
- **Increase battery capacity for night survival**
- **Increase computation for higher speed navigation**
- **Add low power and switched electronics**
- **Increase rover speed to decrease traverse times**
- **Increase wheel torque to improve slope climbing**
- **Eliminate drivetrain hysteresis to improve control**
- **Incorporate subsurface access mechanism**



Mid-Range Navigation

Perception

Terrain evaluation in the mid-field (5-30m) between the resolution of individua obstacle detection (<5m) and orbital maps (30m)

Avoid terrain features like embankments, drainages

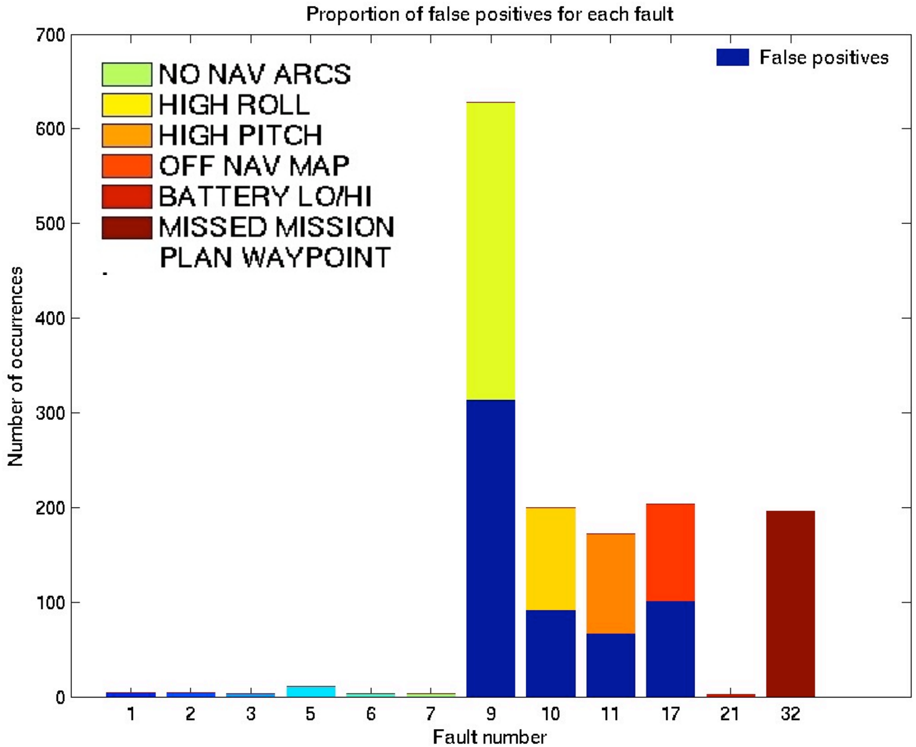
Model terrain :

- Geometrically - slopes, discontinuities
- Semantically - smooth versus rough appearance

Planning

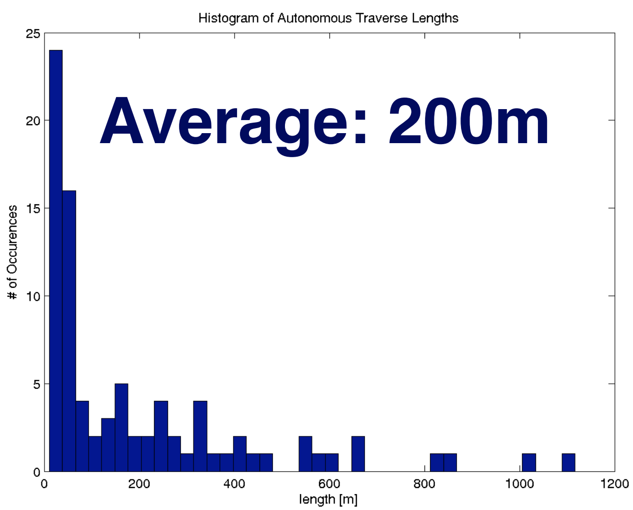
Consistently incorporate near-field, mid-field and orbital terrain information for smooth rover guidance

Fault Detection and Recovery



Traverse duration is currently limited by recoverable faults

Need to monitor internal state, model rover behavior and diagnose



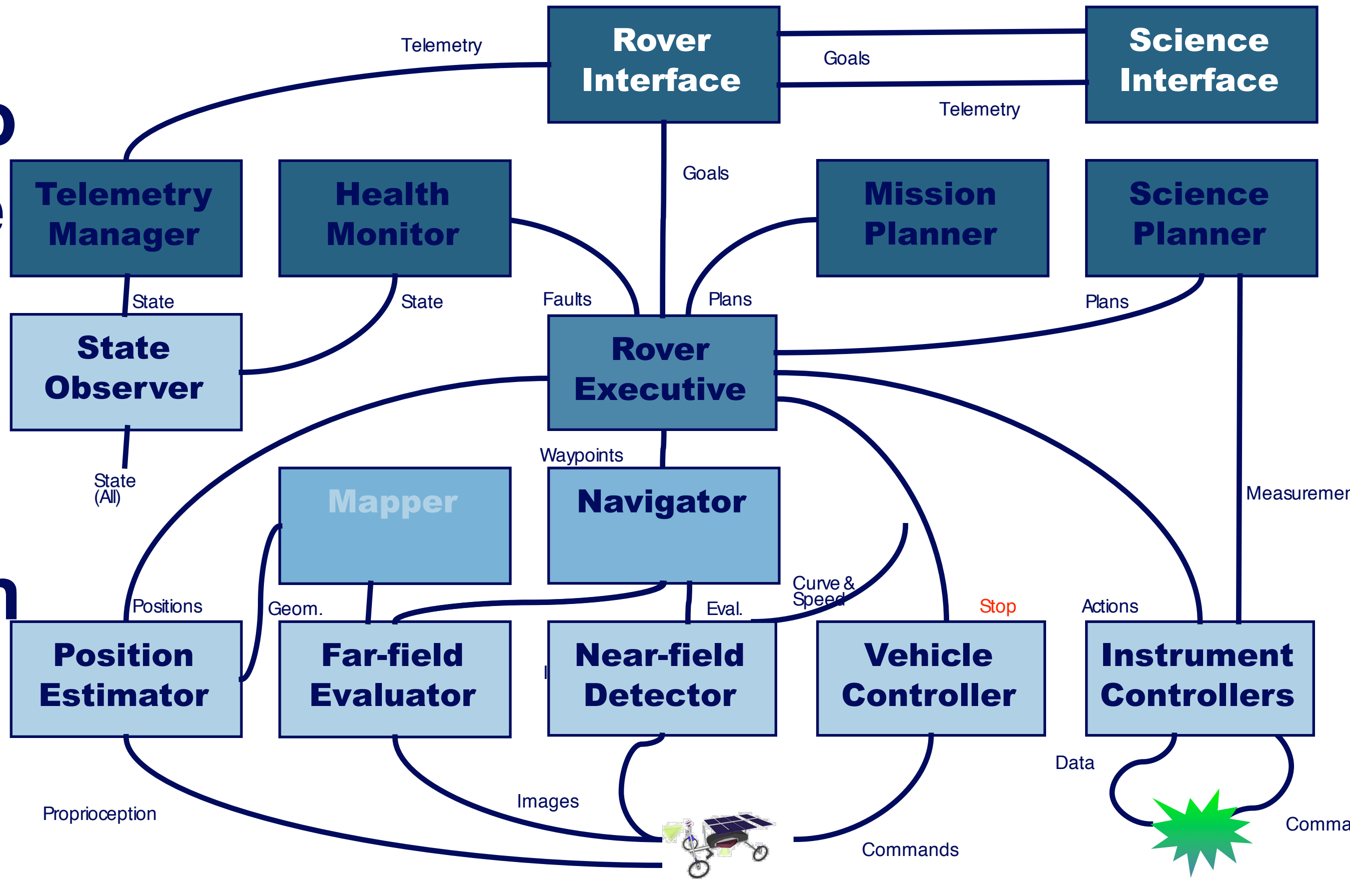
Implement particle filters to detect/identify infrequent faults

Recover by applying contingent actions and global replanning

Mission Plan Execution and Replanning

Planning for communication and science

Resource-cognizant rover executive with fast replanning



Atacama Experiments 2004 & 2005

2004 Functional Integration

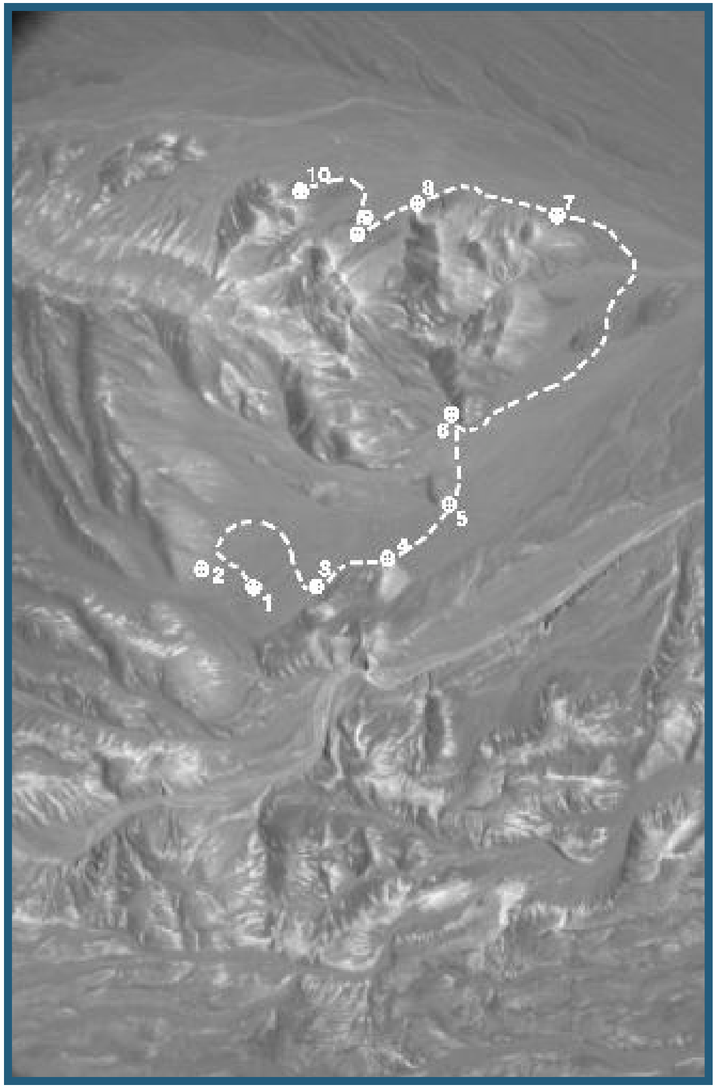
- Rover reconfigured
- Science instrument payload

60 days in September-October

2005 Operational Science

- Rover and software prepared for autonomous exploration
- Complete science payload
- Science team can measure samples and analyze data to answer science questions

100 days in March-June



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Edmond Grin, Geology, NASA ARC/SETI Institute
Andres Guesalaga, Robotics, Pontificia Universidad Católica de Chile
Christian Herrera Lameli , Geology, Universidad Católica del Norte
Dominic Jonak , Robotics, Carnegie Mellon
Arturo Jenson, Geology, Universidad Católica del Norte
Christian Lameli, Geology, Universidad Católica del Norte
Allan Lüders , Robotics, Pontificia Universidad Católica de Chile
Rocco Mancinelli, Microbiology NASA ARC
Dana Martinelli , EventScope, Carnegie Mellon
John Martinelli , Communications, Carnegie Mellon
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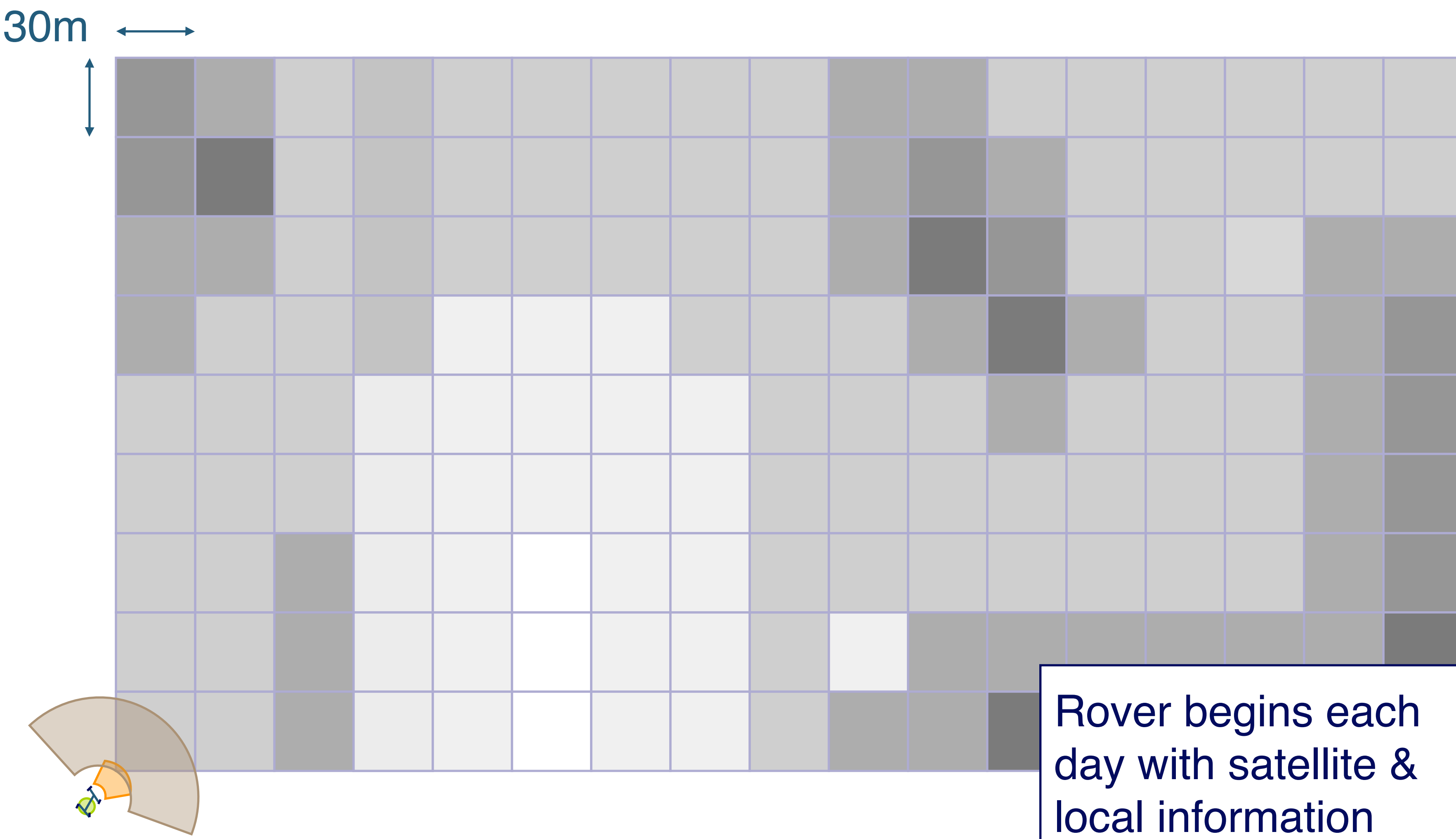
Shmuel Weinstein , Biology, Carnegie Mellon
David Wettergreen, Robotics, Carnegie Mellon
Red Whittaker, Robotics, Carnegie Mellon, Principle Investigator
Hans Wilke, Geology, Universidad Católica del Norte

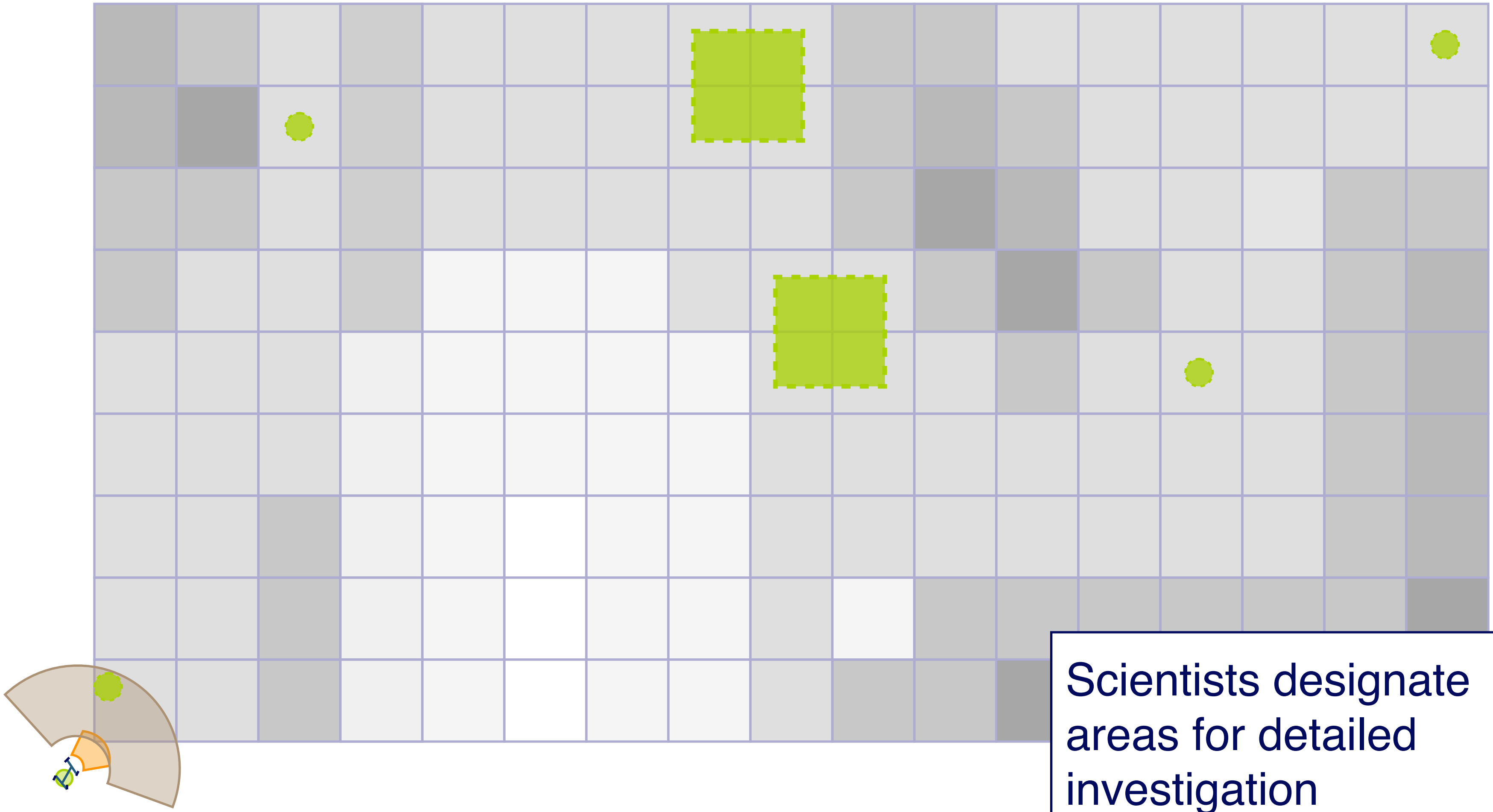
Extras

Science Traverse



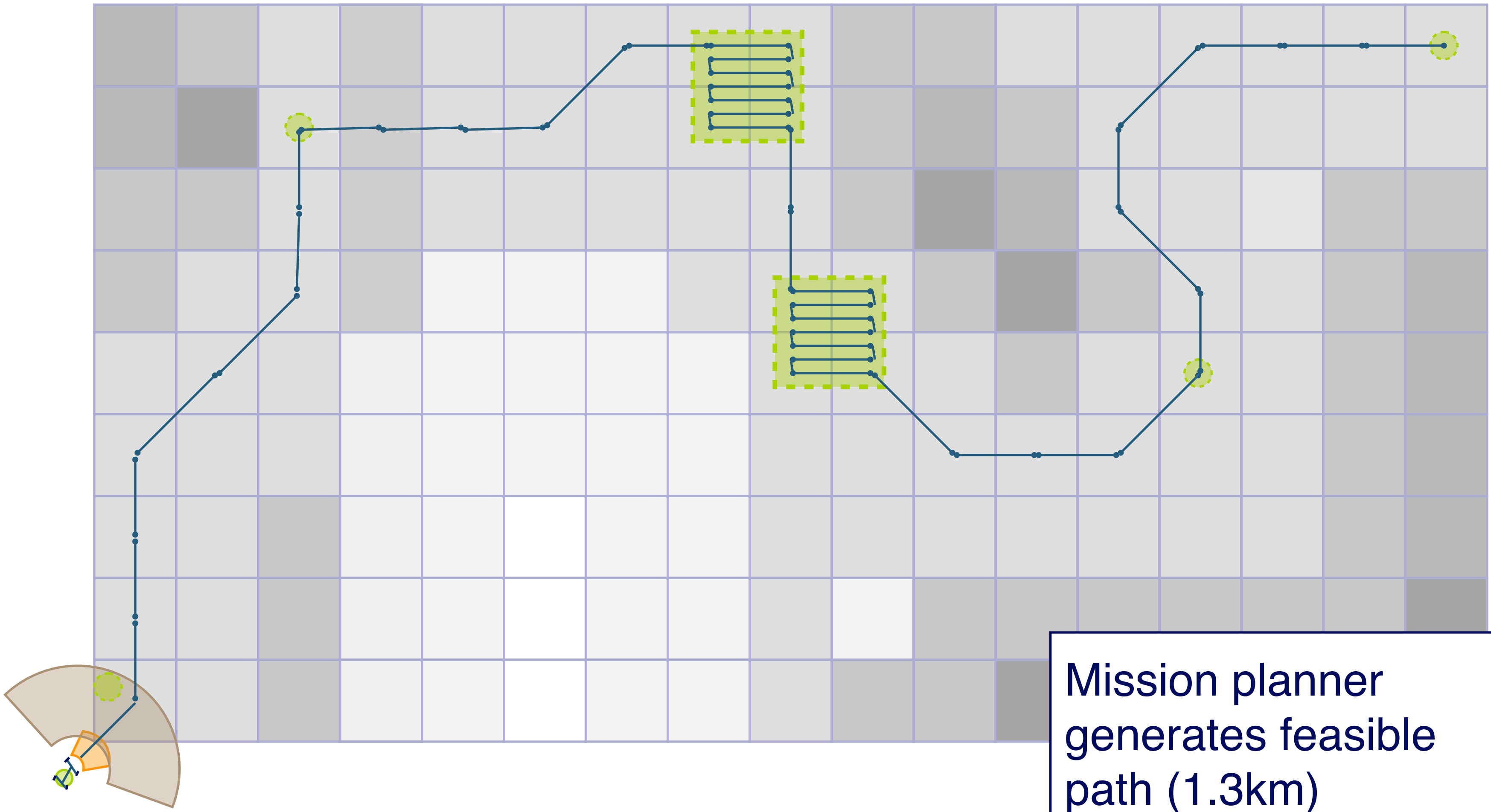
Rover begins each day with satellite & local information

Science Traverse



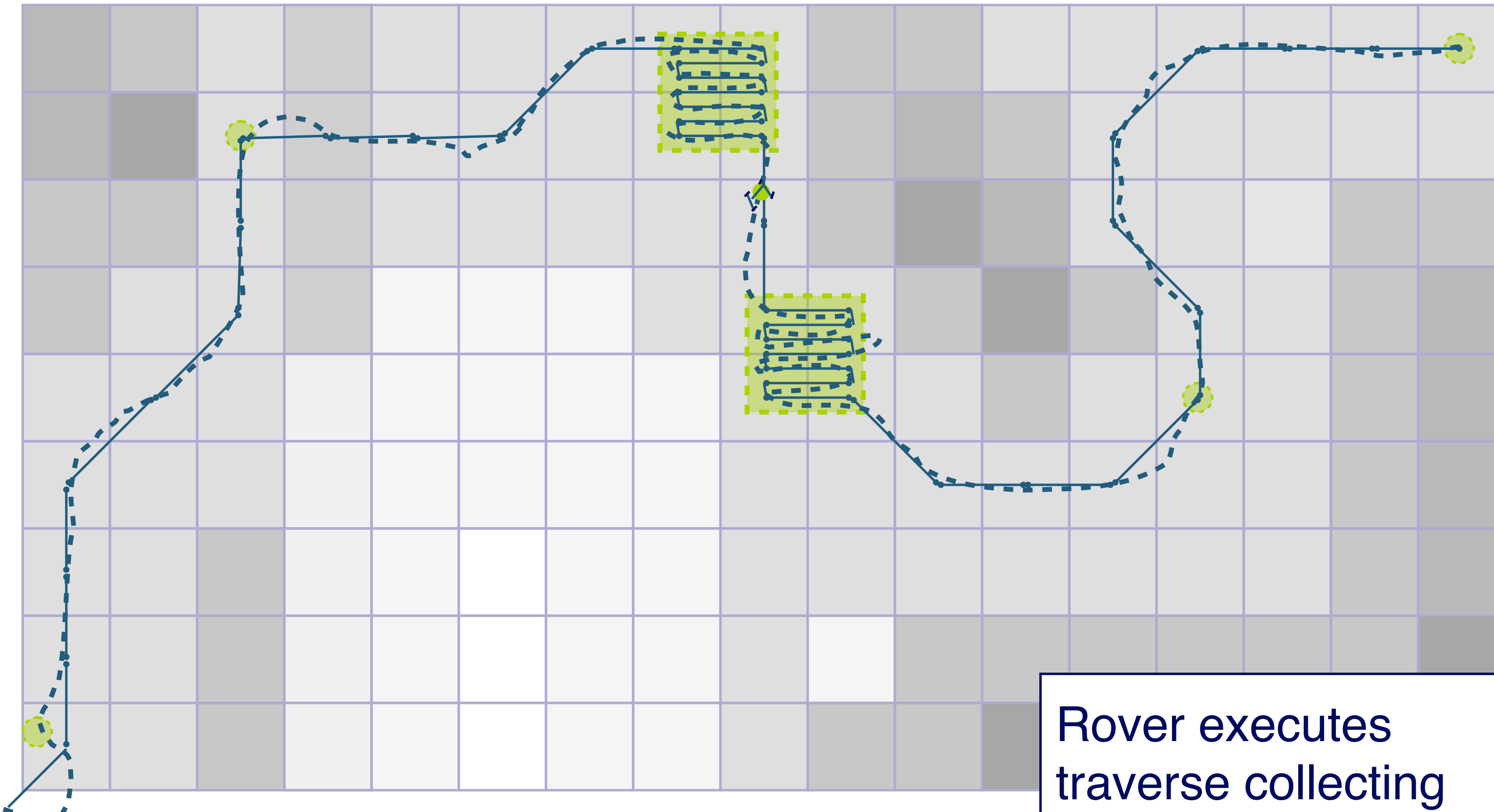
Scientists designate areas for detailed investigation

Science Traverse



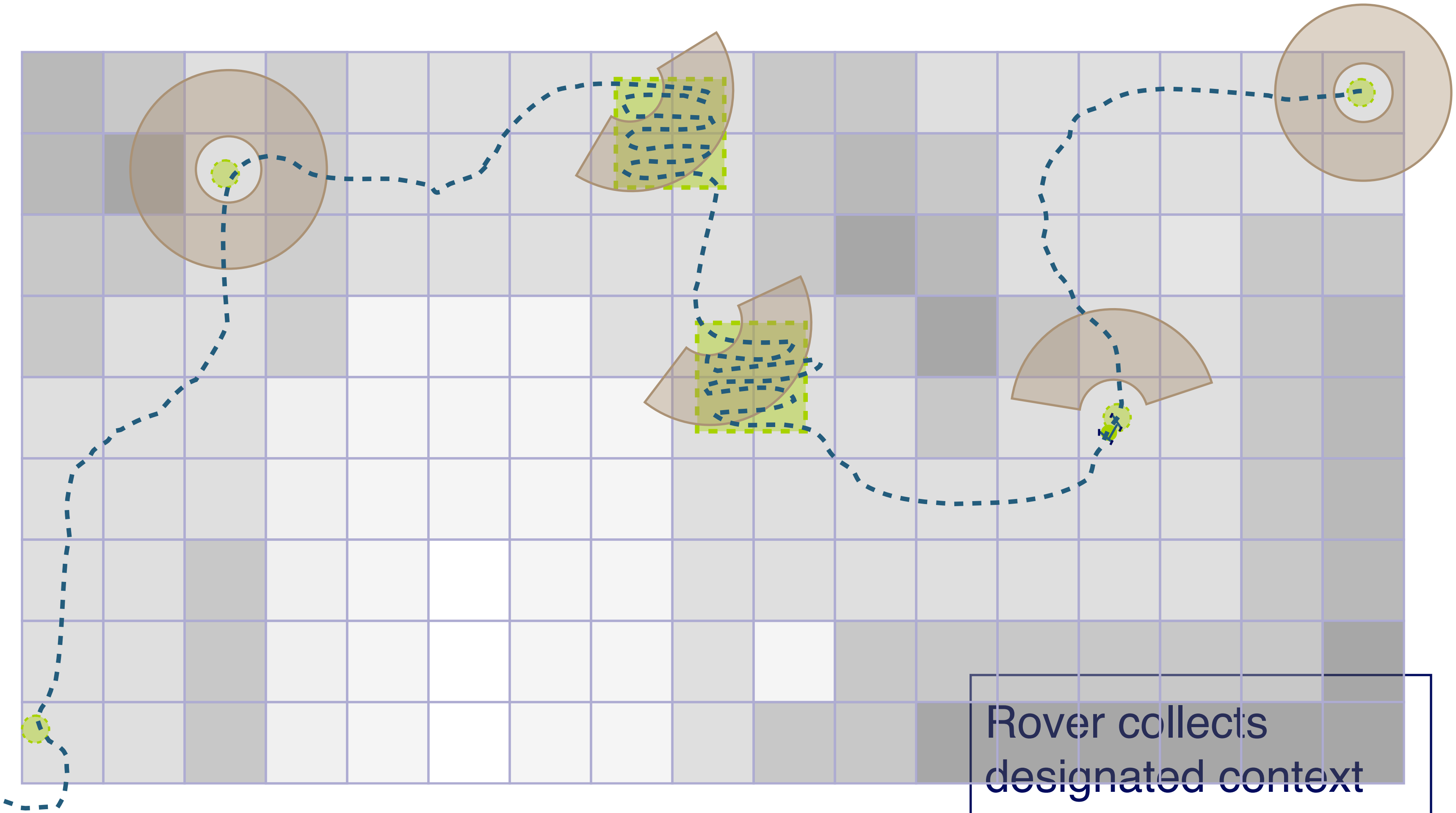
Mission planner generates feasible path (1.3km)

Science Traverse



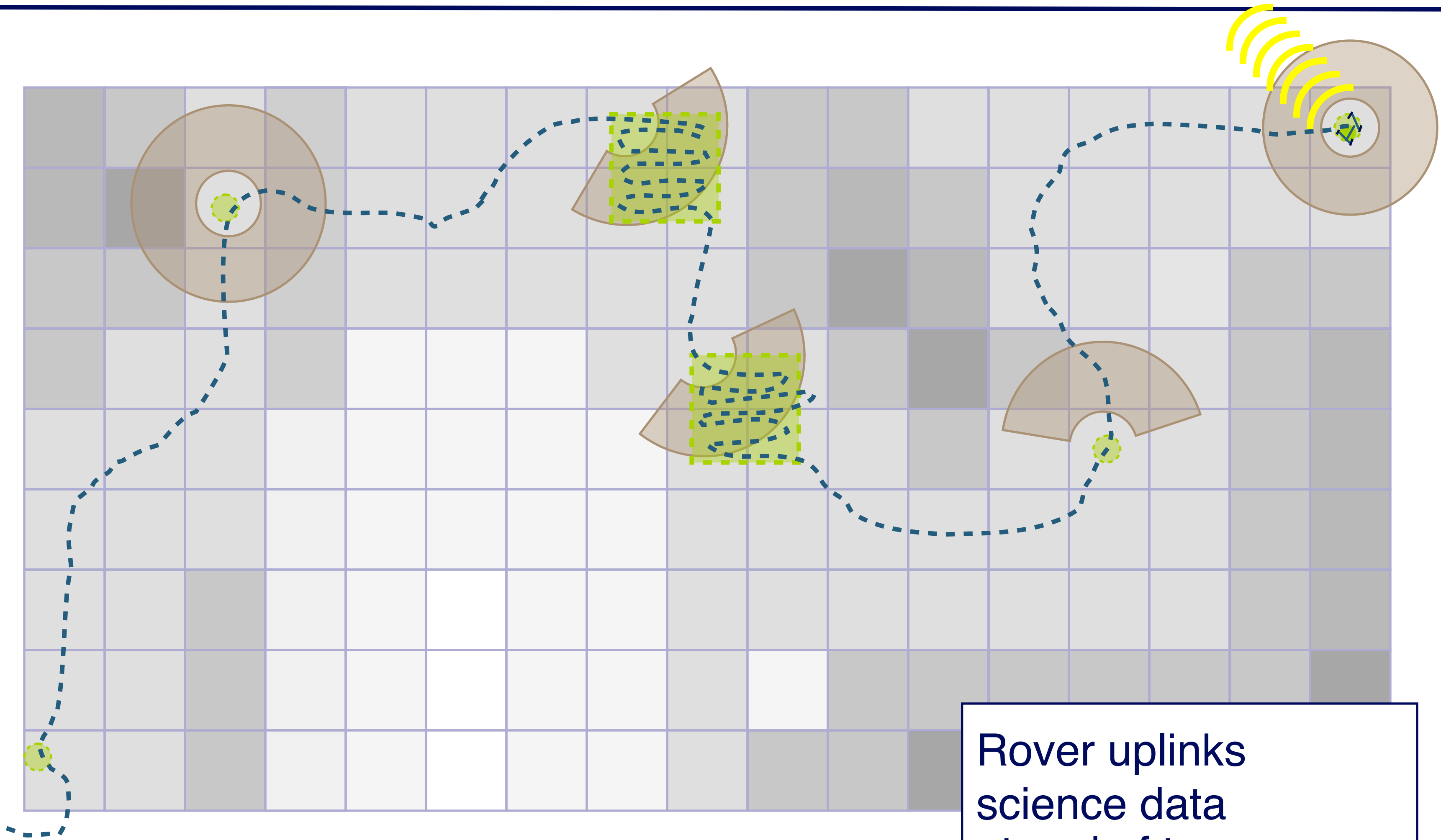
Rover executes traverse collecting survey samples

Science Traverse



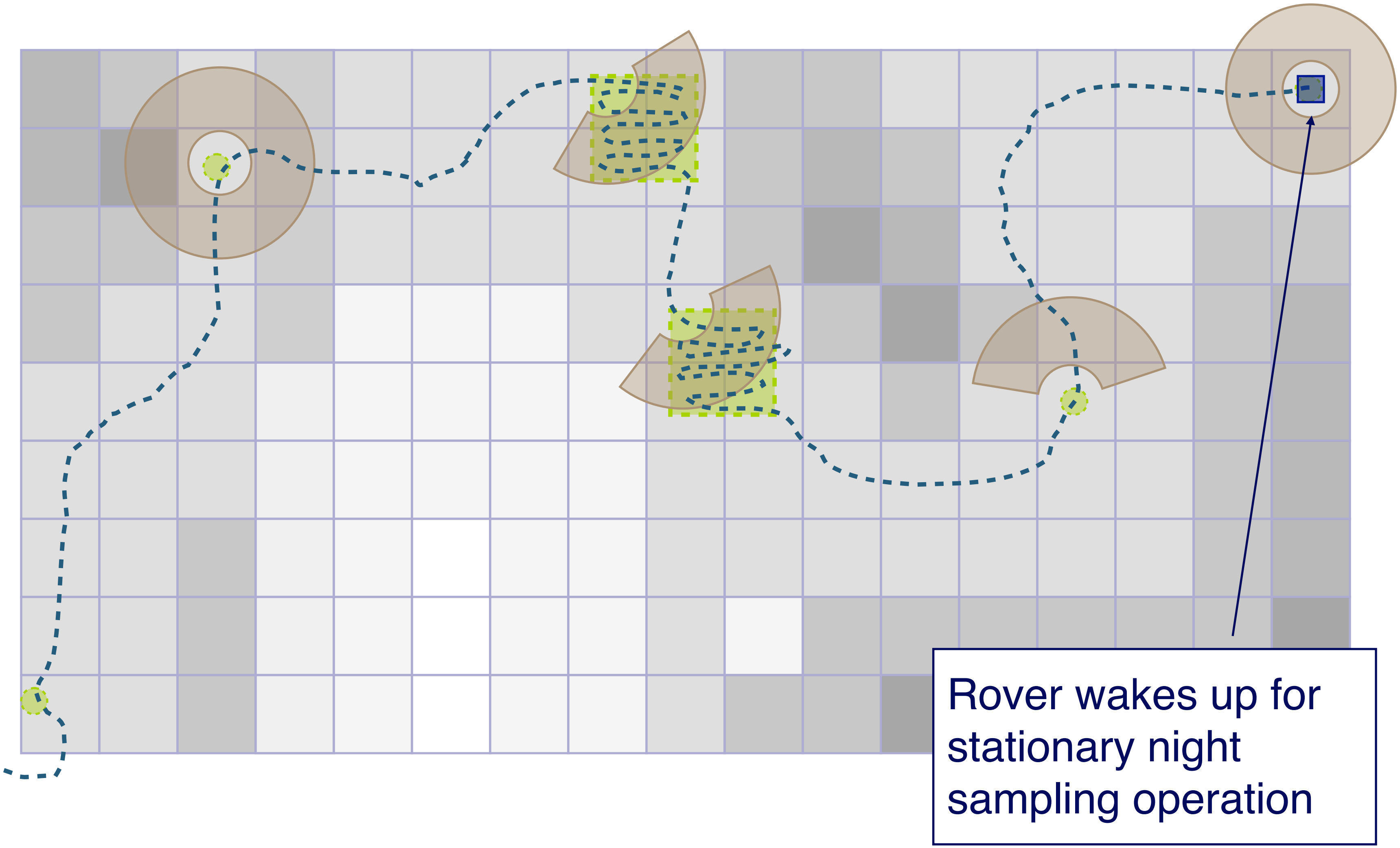
Rover collects designated context imaging

Science Traverse

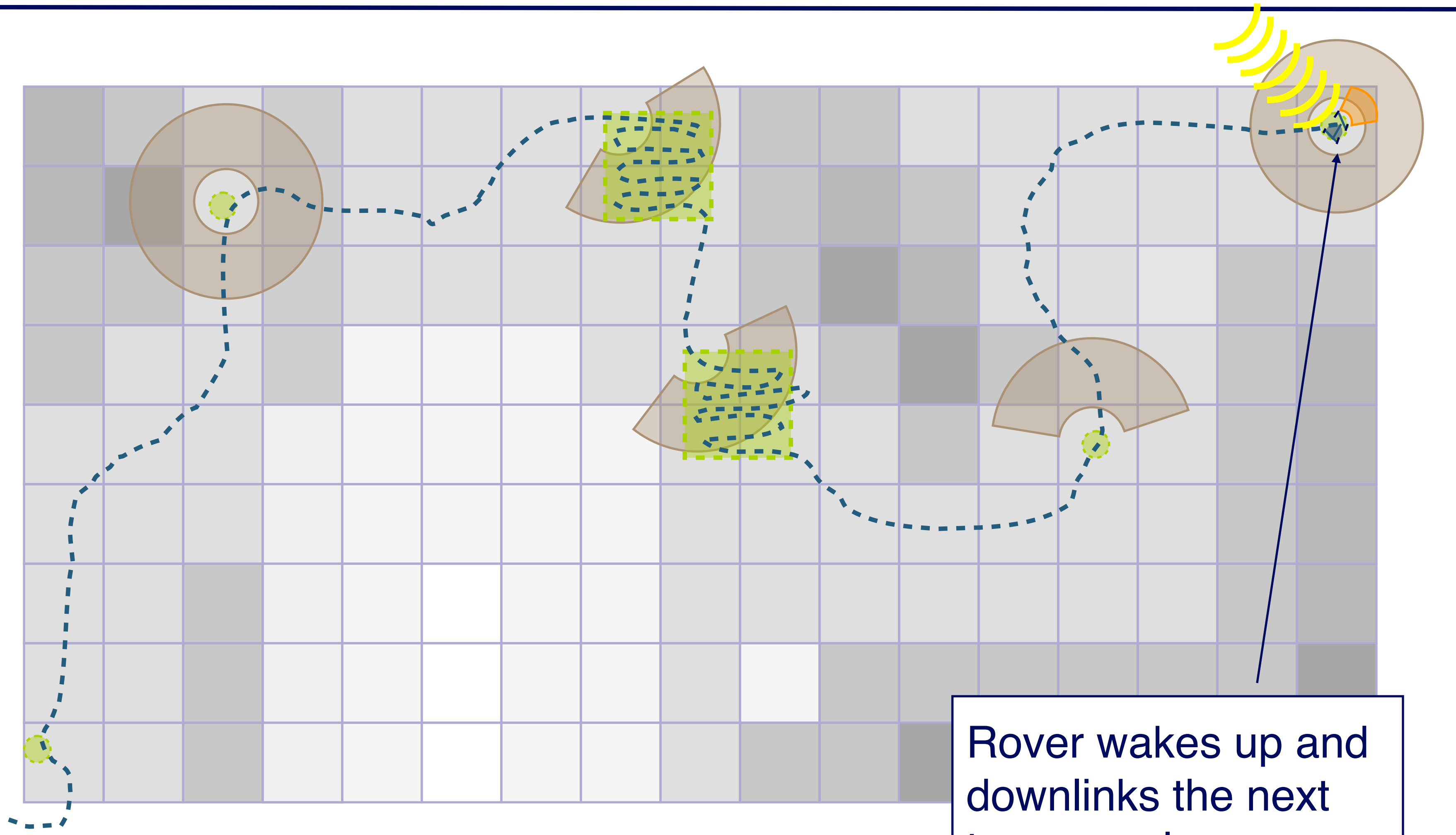


Rover uplinks
science data
at end of traverse

Science Traverse



Science Traverse



Rover wakes up and downlinks the next traverse plan